DESIGN OF AN AMPLIFIER FOR Nd : YAG LASER

by

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LASER TECHNOLOGY PROGRAMME

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

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DESIGN OF AN AMPLIFIER FOR Nd:YAG LASER

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CERTIFICATE

This M.Tech. thesis entitled, "Design of an Amplifier for Nd:YAG Laser" by Mr. Anup Lal Shah, Roll.No. 9011601 has been done under my supervision and has not been submitted elsewhere for a degree.

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Thesis Supervisor

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Thesis Title : Design of an Amplifier for Nd:YAG Laser

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ABSTRACT

Design of single stage Nd:Glass amplifier for a Nd:YAG laser is presented. The system consists of a Q-switched oscillator giving maximum energy of 1 J in a 8 nsec pulse, followed by the amplifier in gain saturation mode. The amplifier is designed to give a maximum energy of 5 J in a 8 nsec pulse. The design parameters for pump cavity, power supply and other electronic circuits are reported. Based on the design parameters, the working of various components is discussed. The overall efficiency which is the product of four efficiency factors is calculated. We find that for our system overall efficiency is 2.88%.

CHAPTER 1

INTRODUCTION

LASER OPERATION

The physical basis of optical-quantum generators, or lasers, is the amplification of light by stimulated emission of radiation. In a system in a state of thermal equilibrium, the number of atoms in any excited state are always less than the number of atoms in the ground state. Whenever radiation containing photons of energy $h\nu=E_f-E_i$ is incident on matter with ground state energy E_i and excited state energy E_f, absorption of photon occurs. The process depends on the number of atoms in the ground state. Spontaneous emission takes place whenever atoms in an excited state decay to lower state. No external radiation is required to initiate the spontaneous emission. If a non-equilibrium condition is created in the system such that the number of atoms in the excited states are more than the ground state, stimulated emission of radiation occurs. In lasers, non-equilibrium distribution of atoms results from optical excitations, current injections, atomic collisions, etc. so that there are more atoms in the upper energy state than the lower energy state, a state of affair known as *population inversion*.

Population inversion can be obtained in several ways. In solid-state lasers (those using crystals or glass), the active atoms are usually excited by optical pumping, that is, by exposing the material to high intensity light. The material absorbs energy from the optical source with the result that the atoms are raised to excited energy states and undergo radiative or non-radiative

materials having absorbing centres with an appropriate set of discrete energy levels suitable for population inversion are called active media. If an e.m. wave of energy $h\nu = (E_f - E_i)$ propagates through such a medium, it is amplified. Analogous to electrical circuits oscillator from an amplifier is made by introducing a suitable positive feedback. The feedback is often obtained by placing the active material between two highly reflecting mirrors. The physical system we consider is a collection of atoms (or molecules) between two mirrors. By some pumping process, such as absorption of light from flash lamp, some of these atoms are promoted to excited states. The excited atoms begin radiating spontaneously, as in an ordinary fluorescent lamp. A spontaneously emitted photon can induce an excited atom to emit another photon of the same frequency and direction as the first. The more such photons are produced by stimulated emission, the faster is the production of still more photons, because the stimulated emission rate is proportional to the flux of photons already in stimulating field. The mirrors of the laser keep photons from escaping completely, so that they can be redirected into the active laser medium to stimulate the emission of more photons. Thus an e.m. wave traveling in a direction along the axis of the cavity will bounce back and forth between the two mirrors and be amplified on each passage through the active material. If one of the two mirrors is made partially transparent, a useful output beam can be extracted. The intensity of the output laser beam is determined by the rate of production of excited atoms, the reflectivities of the mirrors, and the properties of the active atoms. To ensure laser oscillations, however, the population inversion and hence the gain within the

medium must be large enough to overcome various losses, including scattering and absorption of radiation at the mirrors, as well as the "output coupling" of radiation in the form of the usable laser beam. There is therefore a minimum or *threshold* gain which is required to initiate and sustain laser oscillations.

A solid-state optically pumped laser usually emits a series of pulses with random amplitudes, duration and separation typically of 1-10 kw peak power and 1-10 μs duration. Assuming a constant optical pump the population of the upper laser level in the medium builds up. The laser oscillations do not start until the population inversion reaches the threshold value such that net-round trip gain in the laser exceeds unity. When the population inversion crosses the threshold value the oscillations build up increasing the photon flux in the cavity. The increase in the photon flux increases the rate of depletion of the upper laser level population due to stimulated emission, in fact considerably larger than the pumping rate. As a result, the population inversion is depleted below the threshold and in the process a laser pulse is emitted. However when the pulse dies out, the stimulated emission rate again becomes small. At this point the pumping begins to build population in upper level and the cycle repeats and a sequence of pulses would thus be emitted by the laser. Detailed calculations show that the series of pulses is damped and the laser gradually reaches a steady state output. It is important to note that the population inversion exceeds the threshold value only by a marginal amount. A unique method of obtaining energy in a single pulse was suggested by Hallworth. In this method, called *Q-switching*, the stimulated emission is

prevented from depopulating the upper level until sufficient population inversion is reached. This can be done by preventing the feedback using an intracavity switch. Although the energy stored and the gain in the rod are high, the cavity losses are also high, laser action is prohibited, and the population inversion reaches a level far above the threshold for normal laser action. The time for which the energy may be stored is of the order of τ_2, the upper level lifetime. At this time the feedback is restored by opening the shutter, the stored energy is released in the form of a very short pulse of light. Because of the high gain created by the stored energy in the active material, the output pulse rises very rapidly, the resulting pulse giving peak powers several orders of magnitude higher than that for normal oscillations.

Nd:YAG Laser

In Nd:YAG laser about 1% of Y^{3+} is substituted by Nd^{3+}. Pure $Y_3Al_5O_{12}$ is a colorless, optically isotropic crystal which possesses a cubic structure characteristics of garnets. The Nd:YAG laser is a four-level system as shown in Fig.(1). The laser transition, having a wavelength of 1064.1 nm, originates from the R_2 component of the $^4F_{3/2}$ level and terminates at the Y_3 component of the $^4I_{11/2}$ level. At room temperature only 40% of the $^4F_{3/2}$ population is at level R_2; the remaining 60% are at the lower sublevel R_1 according to Boltzmann's law. Lasing takes place only by R_2 ions whereby the R_2 level population is replenished from R_1 by thermal transitions. The ground level of Nd:YAG is the $^4I_{9/2}$ level. There are a number of relatively broad energy levels, which together may be viewed as comprising pump

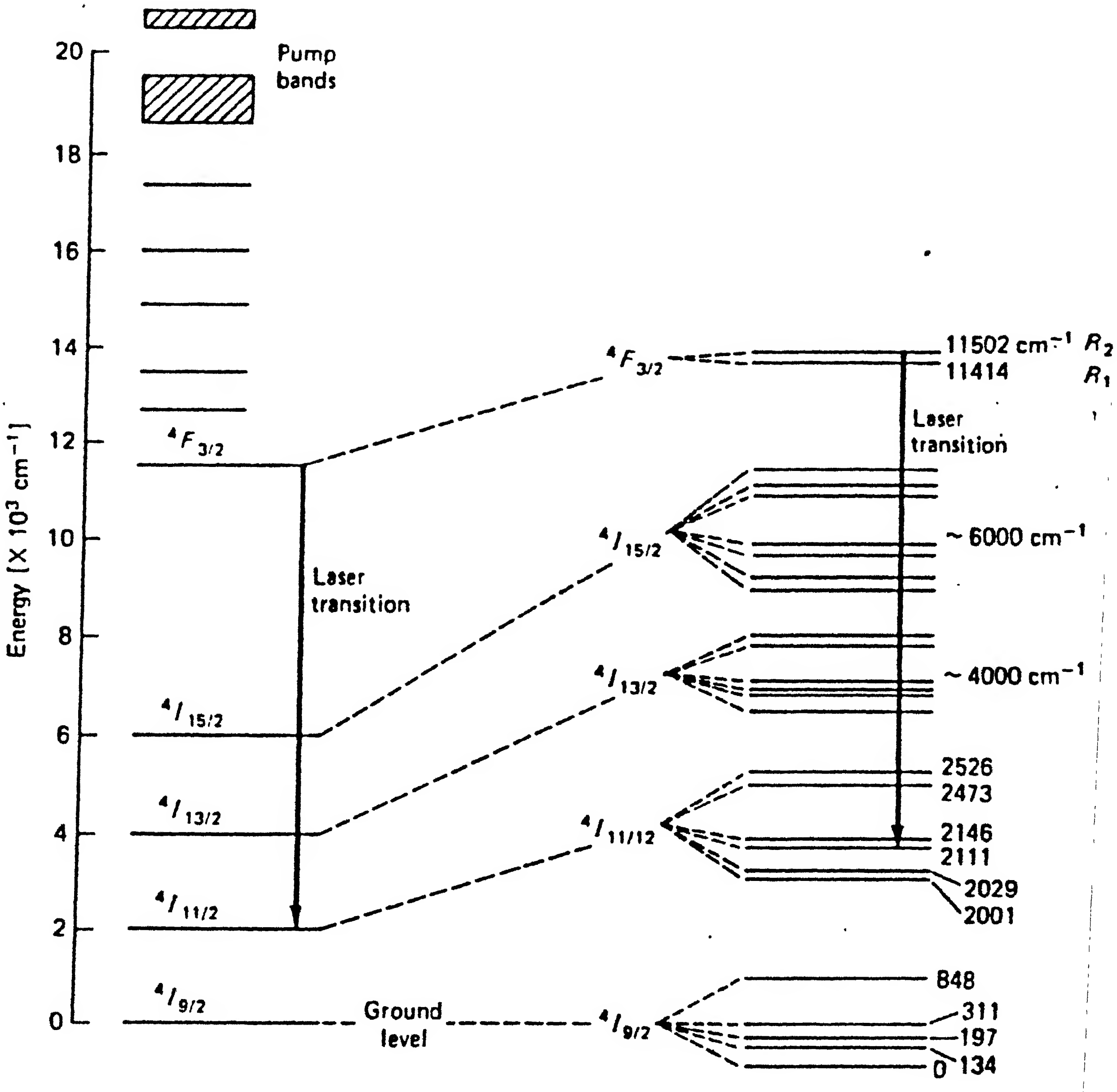


FIG: 1 ENERGY LEVEL DIAGRAM OF Nd:YAG

levels. Of the main pump bands shown, the 0.81 and 0.75 μm bands are the strongest. The terminal laser level is 2111 cm^{-1} above the ground state and thus the population is a factor of $\exp(\Delta E/kT) \approx \exp(-10)$ of the ground state density. Since the thermal level is not populated thermally, the threshold condition is easy to obtain.

The upper laser level, $^4F_{3/2}$, has a fluorescent efficiency greater than 99.5% and a radiative lifetime of 230 μs. The branching ratio of emission from $^4F_{3/2}$ is as follows : $^4F_{3/2} \rightarrow {}^4I_{9/2} = 0.25$, $^4F_{3/2} \rightarrow {}^4I_{11/2} = 0.60$, $^4F_{3/2} \rightarrow {}^4F_{13/2} = 0.14$, and $^4F_{3/2} \rightarrow {}^4I_{15/2} < 0.01$. This means that almost all the ions transferred from the ground level to the pump bands end up at the upper laser level, and 60% of the ions at the upper laser level cause fluorescent output at the $^4I_{11/2}$ manifold.

Laser-Amplifier

The use of laser as pulse amplifiers is of great interest in the design of high-energy, high-brightness light sources. The generation of high-energy pulses is based on the combination of a master oscillator and multistage power amplifier. Fig. 2 shows the block diagram of laser oscillator-amplifier configuration. In this scheme the oscillator generates an initial light pulse of moderate power and energy. This light pulse after passing through the amplifier rod, in which population inversion has been created, gets amplified.

In an oscillator-amplifier system, pulse width, beam-divergence, and spectral width are primarily determined by the oscillator, whereas pulse energy and power are determined by the

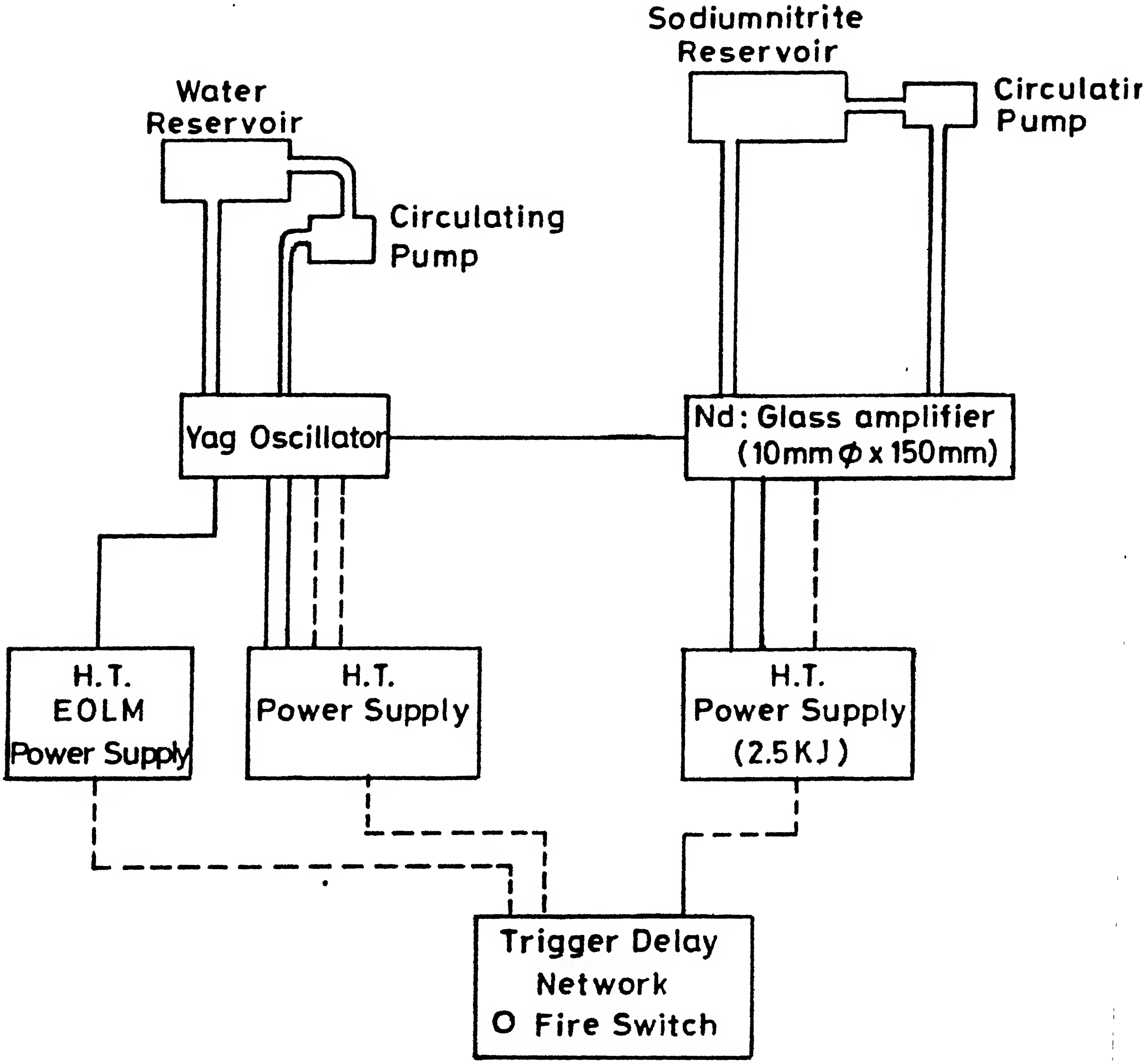


FIG:2 BLOCK DIAGRAM OF THE LASER OSCILLATOR-AMPLIFIER CONFIGURATION

amplifier. The relatively low power in the oscillator state ensures better beam control. Further several optical components like polarizer, mirrors and electro-optic light modulator are used to improve the quality of the beam from an oscillator. These components have their individual breakdown thresholds much below that of the glass material itself. The low power also ensures that these optical components do not get damaged due to high optical fields.

Present Work

We have in our lab Nd:YAG laser, Spectra Physics model DCR-4, which gives maximum peak power of 125 MW in a 8 nsec pulse. We have designed an amplifier using Nd:glass rod (10 mmϕ x 150 mm) for this system. The designing has been done to get a gain of 5 from oscillator-amplifier configuration so that peak power upto 625 MW in a 8 nsec pulse can be extracted. Since the diameter of the glass rod was small (10 mm) the amplifier was designed only for single-shot operation to avoid glass rod damage. The pump cavity for this amplifier was made in CELT Workshop.

The design aspects and design parameters of the amplifier will be discussed in Chapter 2. In Chapter 3 we describe the selection of pump source to pump amplifier, operating characteristics of the pump source, calculation of various parameters required to design the driving circuit for this source, design of power supply and delay circuit for this amplifier system. Mechanical design of the pumping and cooling techniques to cool the glass rod are also discussed. Calculations of various efficiency factors and overall pumping efficiency for the pump

cavity designed are discussed in Chapter 4. Chapter 5 summarizes the results of the present work.

CHAPTER 2

PULSE AMPLIFICATION AND LASER AMPLIFIER

Of primary interest in the design of amplifiers is the gain which can be achieved and the energy which can be extracted from an amplifier. The rod length in an amplifier is determined primarily by the desired gain, while the rod diameter, set by damage threshold considerations, is dependent on the output energy. The deciding factors in designing an amplifier are the gain and energy extraction characteristics, optical damage, premature oscillations due to feedback and wavefront and pulse shape distortion. The optical damage in the material is avoided by increasing the cross-section of successive amplifier stages to keep the power densities below the damage thresholds. This is usually achieved by expanding the output beam of an oscillator using an optical arrangement to fill the cross-section of the amplifier. The premature oscillations in the amplifiers are due to feedback on the system axis and can be avoided by choosing laser rods with ends cut at small angles to their axii.

In high power laser systems, glass host is always chosen for amplifier stages. The reason for this is that the emission lines of ions in glass are inherently broader than in crystals. Since the threshold population inversion is directly proportional to the width of the spectral lines $\Delta\nu$, the laser threshold value for amplification is increased. This broadening offers the possibility of obtaining and amplifying shorter light pulses, and, in addition, it permits the storage of larger amounts of energy in the amplifying medium for the same linear amplification coefficient [Ref. 10]. Thus Nd:Glass rod of length and diameter

depending on gain requirements is prefered over Nd:YAG for an amplifier.

Pulse-Amplification

If W_p, τ_f and t_p are the pumping rate, spontaneous emission time and width of the pulse which passes through the laser rod respectively, then for amplification to occur $t_p \ll \tau_f$, W_p^{-1}. That is, amplification process is based on the energy stored in the upper laser level prior to the arrival of the input signal. As the input pulse passes through the rod, the atoms are stimulated to release the stored energy. If we ignore the effect of fluorescence and pumping during the pulse duration, we obtain for the population inversion

$$\frac{\partial n}{\partial t} = -\gamma n c \sigma \phi \tag{2.1}$$

where, $n = n_2 - \frac{g_2}{g_1} n_1$ is population inversion density, $\gamma = 1 + \frac{g_2}{g_1}$ = 1 for four level system, c is the velocity of light in vacuum, ϕ is photon density and σ is stimulated emission cross-section and g_1 and g_2 are statistical weights of the level 1 and 2 respectively [Ref. 1, 3].

The growth of a radiation pulse traversing a medium with an inverted population is described by the non-linear, time-dependent photon-transport equation, which accounts for the effect of the radiation on the active medium and vice-versa,

$$\frac{\partial \phi}{\partial t} = c n \sigma \phi - \frac{\partial \phi}{\partial x} \tag{2.2}$$

The term on this eqn. describes the rate at which the photon density changes in a small volume of material, it is equal to the

net difference between the generation of photons by the stimulated emission process and the flux of photons which flows out from that region. The latter process is described by the second term on the right of eqn. (2.2).

Consider a square pulse of duration t_p and initial photon density ϕ_o, of a beam of monochromatic radiation, incident on the front surface of an amplifier rod of length ℓ. If the point at which the beam enters the laser rod is designated the reference point x = 0, then the solution for the photon density is

$$\frac{\phi(x,t)}{\phi_o} = \left\{1-\left[1-\exp(-\sigma n x)\right] \exp\left[-\gamma\sigma\phi_o\left(t - \frac{x}{c}\right)\right]\right\}^{-1} \tag{2.3}$$

where n is assumed to be uniform throughout the laser material at t = 0. Therefore the gain in energy for a light beam passing through a laser amplifier of length x = ℓ is

$$G = \frac{1}{\phi_o\ t_p} \int_{-\infty}^{+\infty} \phi(\ell,t)dt \tag{2.4}$$

Introducing eqn. (2.3) into eqn. (2.4) and integrating, we obtain

$$G = \frac{1}{\gamma\sigma\phi_o t_p}\ \ell n\left\{1+\left[\exp(\gamma\sigma\phi_o\tau_o)-1\right]e^{n\sigma\ell}\right\} \tag{2.5}$$

Rewriting eqn. (2.5) in terms of directly measurable laser parameters. To do so let's define the following parameters,

The input energy per unit area can be expressed as

$$E_{in} = \phi_o t_p h\nu \tag{2.6}$$

and a saturation energy density

$$E_s = \frac{h\nu}{\gamma\sigma} \tag{2.7}$$

The physical meaning of the parameter E_s can be understood by multiplying the right-hand side of (2.7) by n. Thus E_s defines the ratio of the energy which can be extracted from the amplifying medium to the small-signal gain coefficient,

$$E_{ex} = g_o E_s = \frac{h\nu n}{\gamma} = \frac{E_{st}}{\gamma} \tag{2.8}$$

From eqn. (2.8) it follows that when an input pulse has an energy density $E_{in} = E_s$, the small signal gain coefficient times the input energy density just equals the maximum energy per volume which can be extracted from the amplifier. For a four level system $\gamma = 1$, from eqn. (2.8), it follows that all the stored energy $E_{st} = h\nu n$ can theoretically be extracted by a signal for a 4-level system.

Introducing eqns (2.6, 2.7) into eq. (2.5), we get G in terms of measurable laser parameters

$$G = \frac{E_s}{E_{in}} \ell n \left\{1+\left[\exp\left(E_{in}/E_s\right)-1\right]G_o\right\} \tag{2.9}$$

Eqn. (2.9) represents a relation between the gain G, the input pulse energy density E_{in}, the saturation parameter E_s, and the small-signal single pass gain $G_o = \exp(g_o\ell)$. Eqn. (2.9) is valid in the regime from small-signal gain to complete saturation of the amplifier. Eqn. (2.9) can be simplified for extreme cases. Consider a low-input, E_{in} such that $E_{in}/E_s \ll 1$, and furthermore $\frac{G_o E_{in}}{E_s} \ll 1$; eqn. (2.9) can be approximated to

$$G = G_o \equiv \exp(g_o \ell) \tag{2.10}$$

In this case, the "low-level gain" increases exponentially with length of the rod, and no saturation effects occur. This, of course, holds only for rod lengths upto a value where the output energy density, $G_o E_{in}$ is small compared to E_s.

For high-level energy densities such that $\frac{E_{in}}{E_s} \gg 1$, eqn. (2.9) gives

$$G \approx 1 + \left[\frac{E_s}{E_{in}} \right] g_o \ell \tag{2.11}$$

Thus, the energy gain is linear with the length of the rod, implying that every excited state contributes its stimulated emission to the output beam. Such a condition obviously represents the most efficient conversion of stored energy to beam energy, and for this reason amplifier design which operates in saturation is preferred. Though the saturation in the medium tends to distort the temporal characteristics of the pulse. The leading edge of the pulse gets amplified more as it extracts energy first leaving the medium with lower gain for trailing edge. Thus the peak of the pulse shifts towards the leading edge.

The pulse width of the input optical beam is also an important parameter determining energy extraction from the amplifiers. In Nd:Glass, the small signal gain is the same for pulse durations in the pico-nano and microsecond regimes. However, the maximum amount of energy which can be extracted by a pulse for a given stored energy depends on the pulse length. This is a result of gain saturation which occurs at different energy densities depending on the pulse length. Gain saturation of a

Nd:Glass amplifier is determined by the laser level lifetime τ_1 which is 1-10 nsec. For pulses much longer than 100 nsec, theoretically all the energy stored in the upper laser level can be extracted by a laser pulse. On the other hand for a pulse which is much shorter compared to τ_1, the population of the lower laser level increases while the population of the upper laser level decreases during the passage of pulse. The filling of the terminal level causes a 'bottleneck' in the stimulated emission process. Energy can be extracted from such a system only to a point where the upper and lower state populations are equal. Therefore, for short pulses, the extracted energy is reduced by a factor of 2.

Design Parameters of Nd:Glass Amplifier

We designed an amplifier using Nd:Glass rod. The dimensions of the rod used are

Length (ℓ)	= 15 cm
Diameter (D)	= 1 cm
Cross-Sectional area (A)	= 0.79 cm^2
Volume (V)	= 11.78 cm^3

Now we will compute the various design parameters for this rod. ($h\nu = 1.86\times10^{-19}$ J, $\sigma = 3.03\times10^{-20}$ cm^2)

For this rod, we have

$$E_s = 6.2\ J/cm^2 \qquad \text{from eqn. (2.7)}$$

and from eqn. (2.8) we get

$$g_o = 0.16\ E_{st}\ cm^{-1} \tag{2.12}$$

For a critically damped lamp pulse of about 300 μs, one can expect typically a 0.5% conversion of pump input energy per unit rod volume to energy stored per unit rod volume [Ref. 1]. Thus

$$E_{st} = 0.005\ E_p$$

where

$$E_p = \frac{\text{Energy stored in the capacitors}}{\text{rod volume}} = \frac{E_{el}}{V}$$

$$\therefore E_{st} = 4.24\times10^{-4}\ E_{el}\ \ J/cm^3$$

From eqn. (2.12) it follows,

$$g_o = 6.79\times10^{-5}\ E_{el}\ \ cm^{-1} \qquad (2.13)$$

and

$$g_o\ell = 1.0\times10^{-3}\ E_{el} \qquad (2.14)$$

Thus for our rod, eqn. (2.9) becomes

$$G = \frac{E_s}{E_{in}}\ \ell n\left\{1+\left[\exp\left(\frac{E_{in}}{E_s}\right)-1\right]e^{10^{-3}E_{el}}\right\} \qquad (2.15)$$

Fig. 3 gives the variation of amplifier gain with pumping energy for an input energy of 500 mJ. Fig. 4 shows the energy output of laser amplifier versus flash-lamp input energy for various laser input energies.

Fig. 2 shows a block diagram of the laser oscillator-amplifier system. It consists of an EOLM (Electro-optic light modulator) Q-switched oscillator followed by the amplifier. The laser rods are pumped by Xenon flash-lamps. The individual power supplies are kept near the respective laser heads and are manually controlled. The firing of the system is controlled by a trigger delay network.The output of the oscillator was fed to the

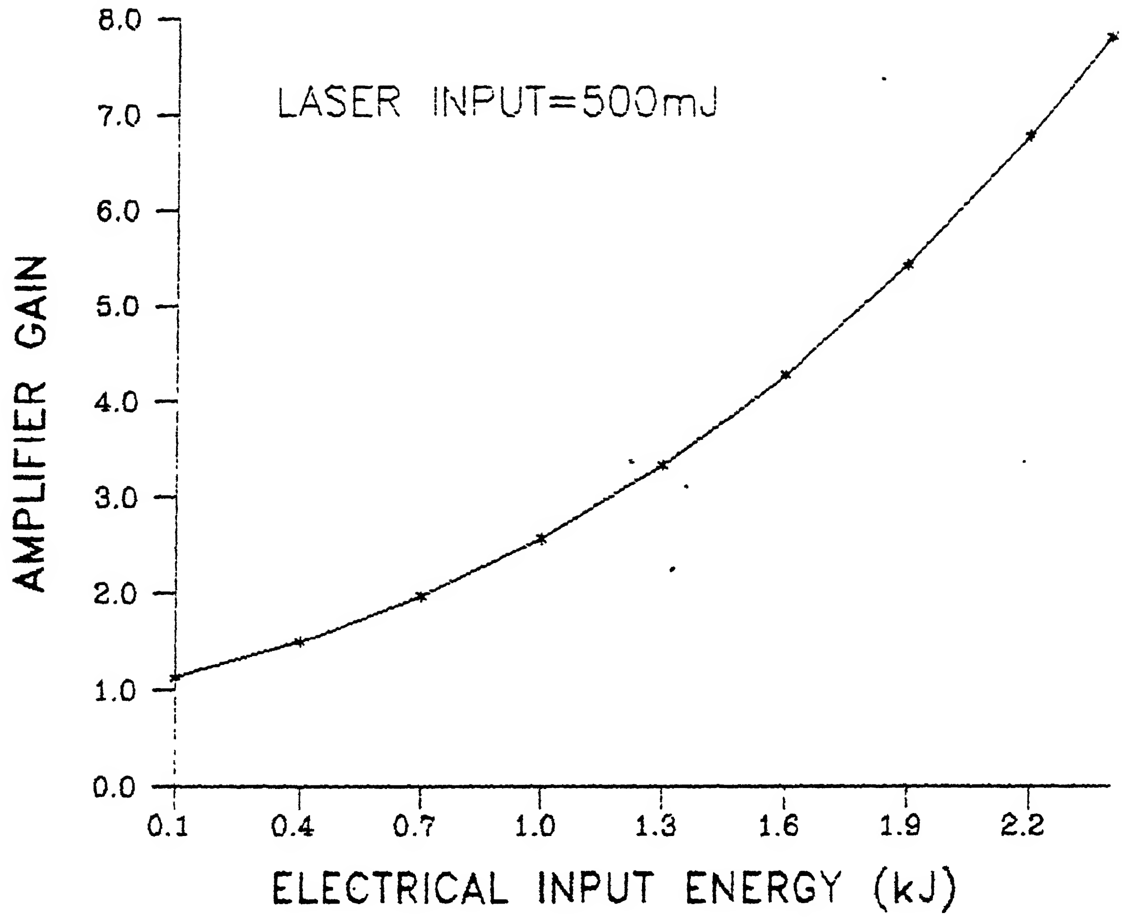


FIG:3 GAIN CHARACTERISTICS OF AMPLIFIER

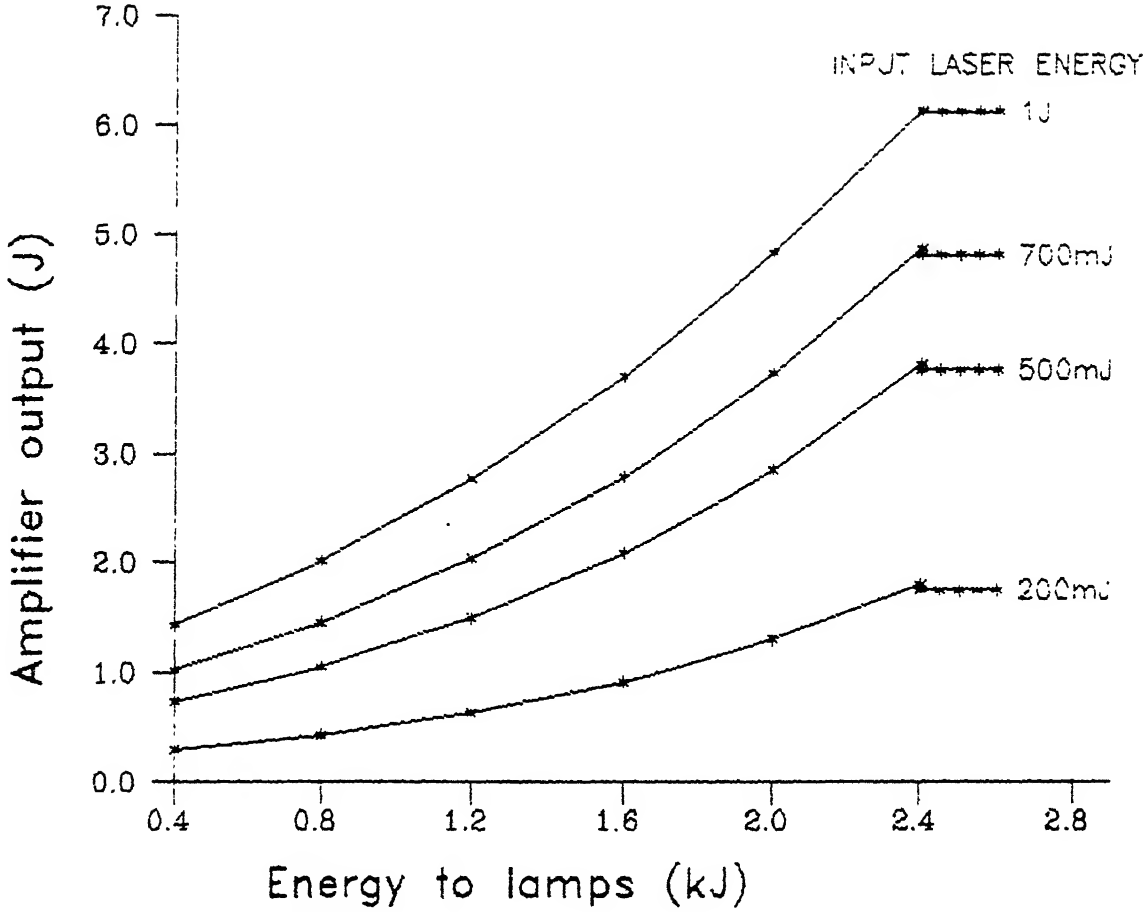


FIG:4 ENERGY OUTPUT OF LASER AMPLIFIER VERSUS FLASHLAMP INPUT ENERGY

amplifier. The amplifier was positioned in such a way that the beam nearly fills the cross-section of the glass rod. Since this rod had normal end faces, it was slightly tilted to avoid reflection feedback on the system axis from its faces to the oscillator.

Since the fluorescence lifetime for amplifier glass, 650 μs and the flash-lamp pulse duration 450 μs are longer than that of oscillator's rod fluorescence lifetime (230 μs), its firing was advanced with respect to the oscillator firing. The gain of the system is a function of this time difference. The delay can be optimized by measuring the output as a function of delay for a fixed input.

For a gain of 5, it follows from Fig. 4 that E_{el} = 1.8 KJ for an input energy of 500 mJ. Thus from eqn. (2.13), the gain coefficient is

$$g_o = 0.12 \text{ cm}^{-1}$$

and the population inversion attained in the active medium is

$$N = \frac{g}{\sigma} = 4.03 \times 10^{18}/\text{c.c.}$$

To estimate the cross-section for calculating volume of the active medium, burn patterns were taken. The central bright portion of the burn pattern was taken as the cross-section of the active medium. For our rod we had the area of this bright portion ~0.28 cm^2 and hence volume of the active medium is ~4.24 cm^3 and hence the total population inversion in the active medium is ~1.71×10^{19}. Thus the stored energy in the medium being given by $E_{st} = Nh\nu$ is 3.18J. For a gain of 5, the expected output energy

is 2.5 J. Since a large fraction of energy is extracted, it can be concluded that the amplifier is driven into saturation.

CHAPTER 3

OPTICAL PUMP SYSTEM OF AMPLIFIER

In optically pumped solid-state lasers the light source must supply the maximum possible output in the spectral region that can be absorbed by the laser material. Electrical current, either continuous or pulsed, is supplied to the pump source and converted into optical radiation. The light source and laser material are contained in a pumping arrangement which concentrates the light from the pump source onto the laser material. The three components which together comprise the optical pump system of a solid-state laser are

(a) The pump source

(b) The power supply

(c) The pump cavity

3.1 The Pump Source

In the application of light sources for pumping lasers, the primary objective is to convert electrical energy to radiation efficiently and to generate high-radiation fluxes in given spectral bands. The most efficient laser pump lamp will produce maximum emission at wavelengths which excite fluorescence in the laser material, and produce minimum emission in all spectral regions outside of the useful absorption bands.

Optical pumps for solid-state lasers can be categorized into noble gas and metal vapour discharge lamps, filament lamps, laser diodes, and pumps not based on electricity as the prime power source, such as the sun, chemical flash bulbs and radiation

obtained from detonations. Flashlamps used for laser pumping are essentially long arc devices designed so that the plasma completely fills the tube. A flashlamp consists of a linear or helical quartz tube, two electrodes which are sealed into the envelope, and a gas fill. Standard linear lamps have straight discharge tubes with wall thickness of 1 to 2 mm, bore diameters between 3 mm and 19 mm, and lengths from 15 cm to 1 m.

A lamp's spectral output is determined largely by current density (i.e., the amount of current flowing per unit of cross-sectional area of the lamp) defined by $4i/\pi d^2$, where d is the bore diameter of the lamp and i the current through the lamp. In a pulsed lamp the amount of current flowing changes with time, increasing from zero (or a very low value) to a maximum and then decreases again, each time the lamp is pulsed. Consequently the spectral output will also vary with time and any graphical representation of this is usually time-integrated plot of the lamp's output.

The Xe flashlamps are commonly used to pump Nd:Glass lasers. The reasons are varied but include the following considerations :

* The output of Xe flashlamps extends spectrally from the ultraviolet region to the infrared, thus overlapping the absorption spectra of Nd^{3+}.

* Xe flashlamps are high-brightness sources and because of a high efficiency for converting electrical to spectral output they can provide the flux necessary to achieve reasonable stored-energy densities in Nd:glass lasers.

* The lifetime limits of Xe flashlamps are fairly well understood; such lamps are durable and have, when driven properly, an acceptable lifetime for present Nd:glass laser system.

Fig. 5 shows the experimental configuration used to take the absorption spectrum of Nd:Glass. This spectrum was taken using a CW Xenon lamp. Fig. 6 shows the absorption spectrum of Nd:Glass. In Fig. 7 the spectral emission of a Xenon flashtube is plotted for two current densities. As a result of high current densities, the line structure is in this case masked by a strong continuum. From Fig. 7 it also follows that a high current density shifts the spectral output toward the shorter wavelengths. A comparison of Fig. 6 and Fig. 7 shows that Xenon flashlamps are suitable to pump Nd:Glass. In our design we have used an elliptical reflective cavity which can reflect light from the lamp directly onto the rod. Large lamp bore diameters lead to poor reflection efficiency; on the other hand small bore diameters limit power input into the lamp. The optimum compromise is usually to have the lamp of bore diameter roughly equal to the rod diameter.

Operating Characteristics of Pulsed Lamps

Driving Circuit

The basic pulsed lamp driving circuit is shown in Fig. 8. When the lamp is non-ionised it has a very high impedance around 10 MΩ or more and so initially all the current from the power supply unit flows into capacitor C. If the voltage across the capacitor reaches a value equal to the self-breakdown voltage of the lamp then ionisation of the gas in the lamp starts to occur

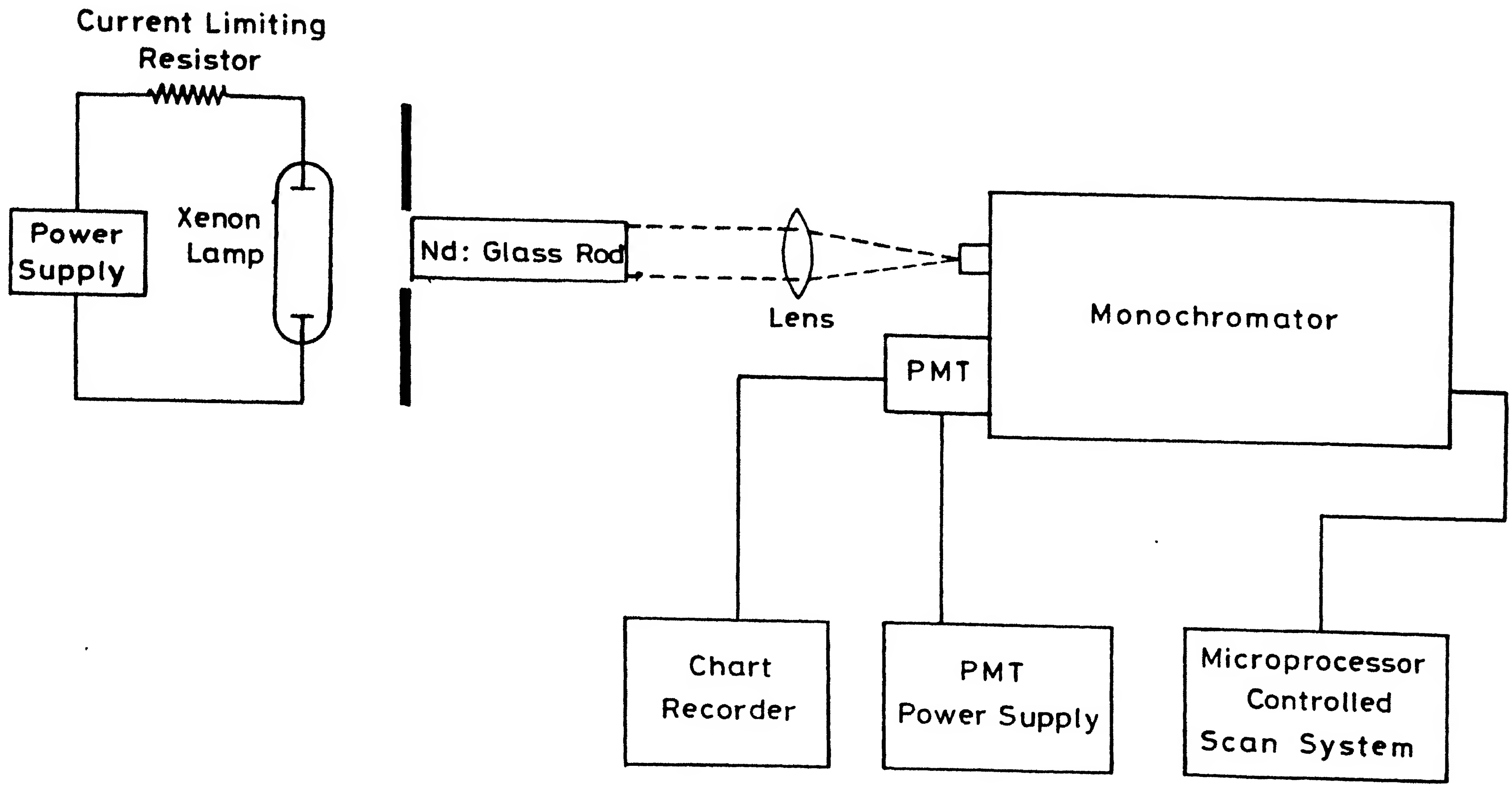


FIG:5 EXPERIMENTAL CONFIGURATION USED TO MEASURE ABSORPTION SPECTRA OF Nd:GLASS

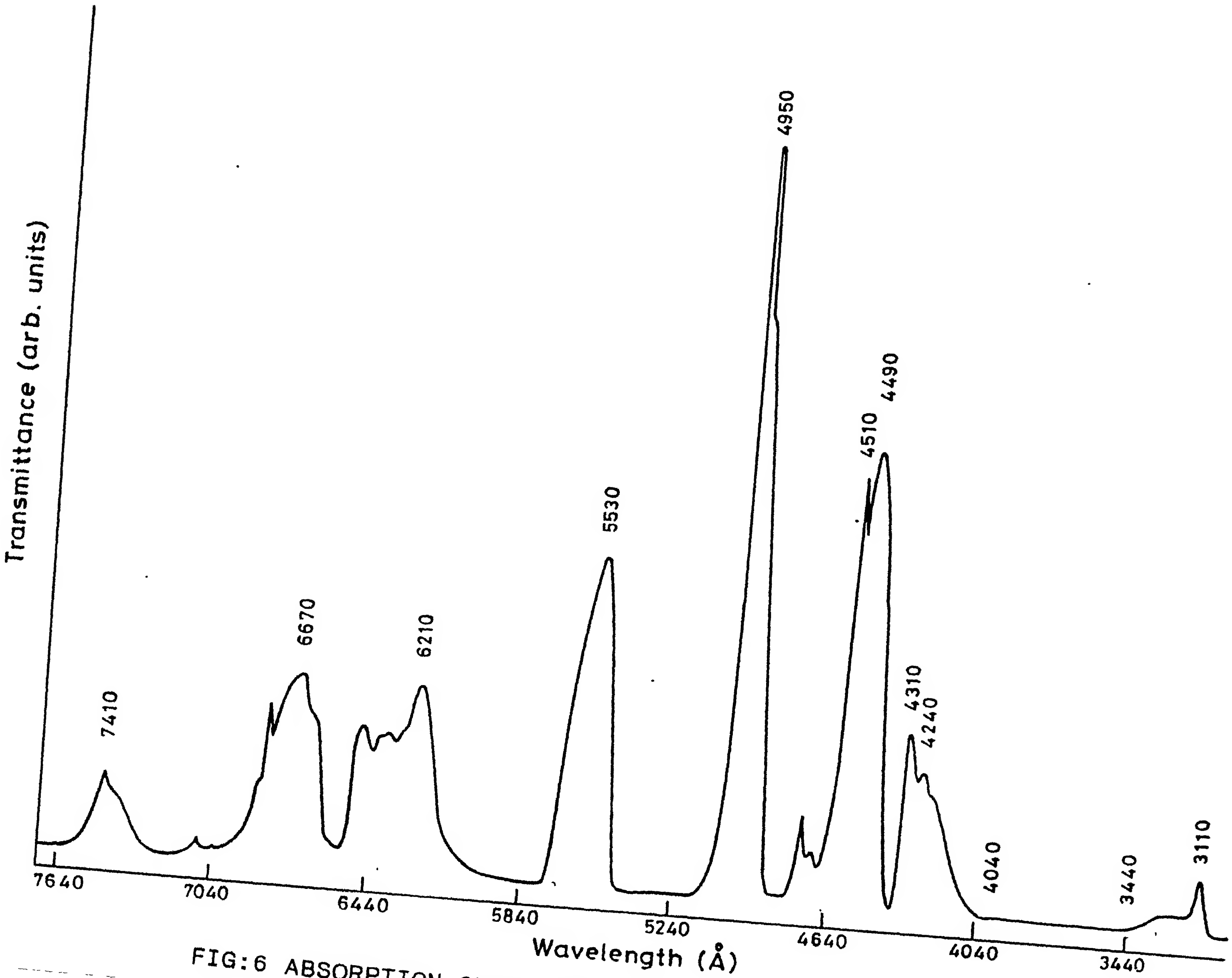


FIG:6 ABSORPTION SPECTRUM OF Nd IN SILICATE GLASS

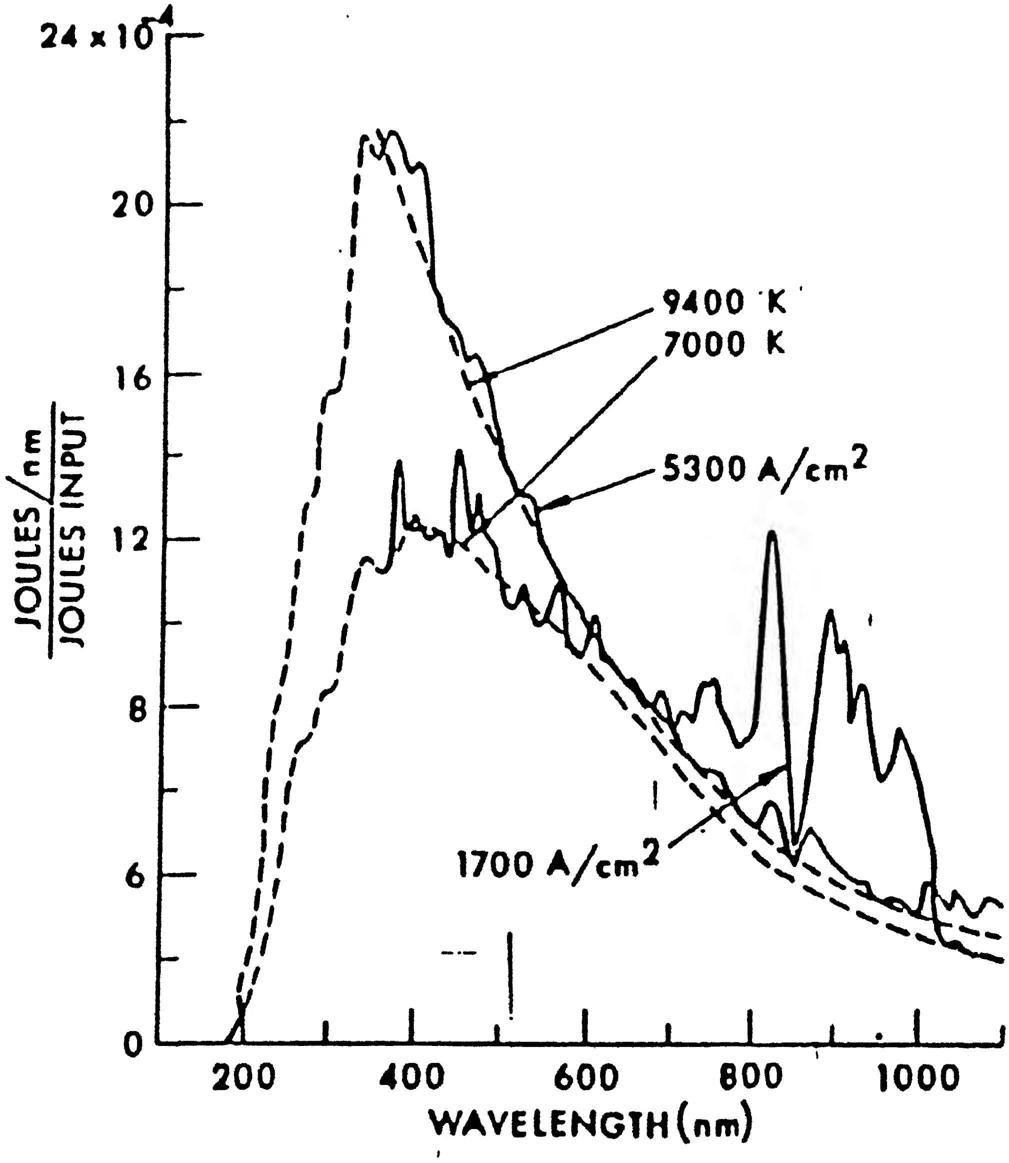


FIG:7 SPECTRAL EMISSION OF A XENON FLASH-TUBE

and so its impedance begins to fall. Quickly a low impedance path forms between the electrodes of the lamp as more gas atoms are ionised. Current now flows from the capacitor into the lamp and the impedance of the lamp continues to fall, dropping right down to about 1Ω or less. If sufficient charge is available the plasma of ionised gas in the lamp completely fills the bore. Eventually all of the energy stored in the capacitor is expended and the lamp returns to a de-ionised state. Conduction through the lamp ceases and the power supply unit begin to recharge the capacitor - and so the process continues.

Three distinct regimes in the operation of a lamp will now be considered. Ref. [5].

(a) Initial arc formation - or `triggering'

(b) Unconfined discharge regime of the plasma, and

(c) Confined (wall-stabilised) discharge regime of the plasma

Triggering

The basic triggering technique shown in Fig. 8 is not a practical one. Self-breakdown voltages of pulsed lamps are high and are not always repeatable. If however a separate triggering transformer is used to apply a brief high voltage pulse to the lamp-typically 10 to 25 KV in the microsecond range then the power supply unit and the capacitor only need to handle voltages much lower than the breakdown voltage, and the energy of the pulse will be defined since the capacitor will charge to a defined voltage before each flash. Triggering is also more reliable. The two most popular types of triggering are known as parallel triggering

and series triggering.

Parallel triggering

With this method the triggering transformer is external to the lamp driving circuit. Lamp current does not therefore flow through the secondary winding and so external triggering transformers are relatively small and inexpensive. The high voltage triggering pulse is applied to the lamp via a nickel wire, running the length of the lamp and usually with several loops around the lamp body. The circuit is shown in Fig. 9.

Series triggering

The series technique uses a transformer in series with the lamp. Consequently the secondary winding has to be capable of handling the lamp current once triggering has taken place. Such transformers are thus more expensive. A great advantage of the method, however, is than no high voltages are exposed external to the lamp. Insulation and lamp changing problems are therefore simpler. A typical circuit is shown in Fig. 10. The use of a ground plane greatly eases triggering problems. This can take the form of a wire, similar to a trigger wire, but attached to one lamp terminal. Alternatively the laser cavity will often act as a suitable ground plane. In many instances the saturated inductance of the secondary winding of the trigger transformer forms the inductance of a single LC network.

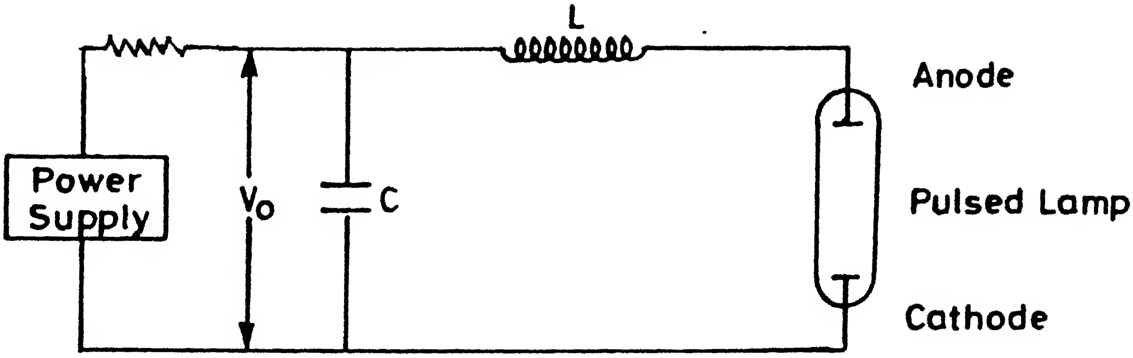


FIG:8 SIMPLE PULSED LAMP DRIVING CIRCUIT

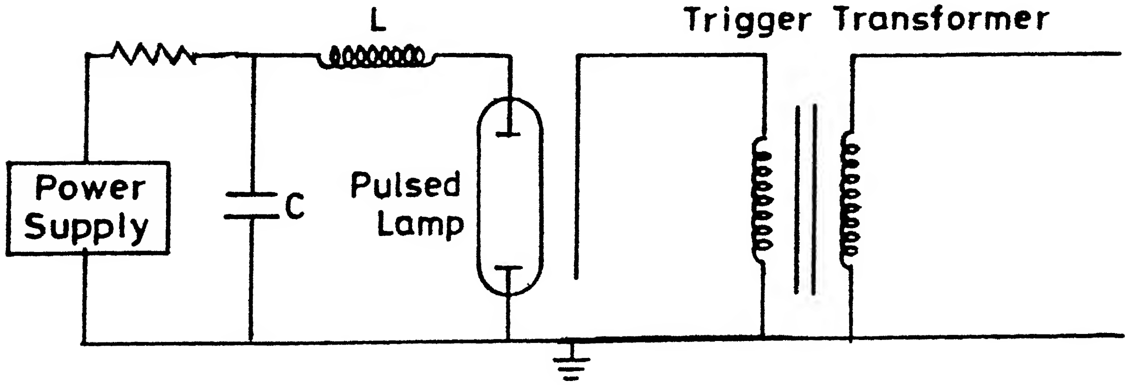


FIG:9 TYPICAL PARALLEL-TRIGGERING CIRCUIT

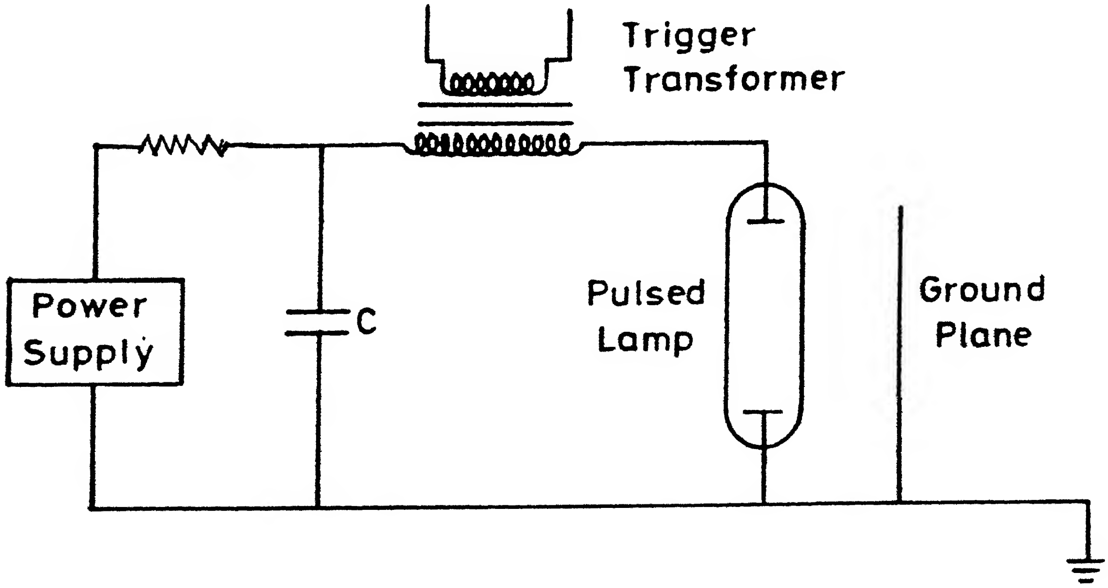


FIG:10 TYPICAL SERIES- TRIGGERING CIRCUIT

Unconfined discharge regime of the Plasma

Once triggering has taken place the plasma grows, current through the lamp rapidly increases and the voltage drop across it rapidly falls, as a result the lamp's impedance quickly decreases. During this stage (some 20 percent of the rise time of the current pulse through the lamp) the characteristics of the arc are not influenced by the inner wall - i.e., the discharge is unconfined. If sufficient energy is available the plasma grows until it fills the bore of the lamp and becomes what is termed 'wall stabilised'.

Confined (wall stabilised) discharge regime of the Plasma

When the arc reaches this stage it is characterized by high current and high power density, and can be described as having an impedance with the following relationship to time :

$$K_o[t] = \pm V(t)\ [i(t)]^{-1/2} \tag{3.1}$$

where : $V(t)$ = voltage across the lamp at time t, in volts; $i(t)$ = current through the lamp at time t, in amps; $K_o(t)$ = arc impedance parameter at time t, in ohms-amps$^{1/2}$. The sign of the expression is chosen to be the same as the sign of i. $K_o(t)$ is a function of the time-dependent size of the arc and the nature and fill pressure of the gas in the lamp

$$K_o(t) = \frac{1.28L_A}{d_A(t)} \times \left(\frac{P}{N}\right)^{1/5} \tag{3.2}$$

where : L_A = arc length, in cm.; $d_A(t)$ = arc diameter at time t, in cm.; P = gas fill pressure in the lamp, in Torr; N = a constant dependent on gas type (Xenon 450; Krypton 805)

A good approximation can be reached, avoiding dealing with the time dependent equations (3.1) and (3.2) [which requires computing techniques], by assuming that the diameter of the arc is always equal to the diameter of the bore of the lamp (d) - i.e., by assuming that $d_A(t)$ does not have time dependence. In fact, in general the time taken to reach stabilisation is less than one-hundredth of the pulse width.

Thus equation (3.2) becomes

$$K_o = 1.28 \frac{L_A}{d} \times \left[\frac{P}{N} \right]^{1/5} \tag{3.3}$$

K_o can now be referred to as the impedance constant of the lamp. This is constant for any given lamp because K_o depends only upon the lamp's physical dimensions and the type and pressure of gas fill. K_o is a critical parameter in describing a pulsed lamp

$$V(t) = \pm K_o[i(t)]^{1/2} \tag{3.4}$$

In practice, pulsed lamps are often driven by a single-stage inductance-capacitance(LC) network as shown in Fig. 8. The equations describing this network are :

$$E_o = \frac{CV_o^{\ 2}}{2} \tag{3.5}$$

$$t = (LC)^{1/2} \tag{3.6}$$

$$C = \left[\frac{2E_o\alpha^4 t^2}{K_o^{\ 4}} \right]^{1/3} \tag{3.7}$$

$$Z_o = \left[\frac{L}{C} \right]^{1/2} \tag{3.8}$$

$$T = 3t \tag{3.9}$$

where E_o = energy stored in capacitor C, in joules; C = capacitance of capacitor C, in farads; L = inductance (henries); t = time constant of the circuit, in seconds; Z_o = impedance of circuit, in ohms; T = pulse length in second (at 1/3 peak height); α = damping parameter.

Fig. 11 shows solutions of these equations for i(t) with different values of α. For value $\alpha = 0.8$ it can be seen that there is no reversal of the current in the circuit. This is known as a critically damped circuit in which the pulse length T is defined as 3t or 3x square root of LC. In practice, the laser pulse length would be shorter than the value T.

From this analysis it is seen that for a given pulsed lamp and a specified pulse energy and pulse width there is only one value each for C, L and V_o that will result in critical damping, a requirement for maximum efficiency and lamp life.

An approximate value of peak current can be calculated from :

$$i_{max} = \frac{V_o}{Z_o + Z_L} \tag{3.10}$$

where Z_L is the impedance of the lamp in ohms. and can be derived from,

$$Z_L = \frac{\rho L_A}{\text{cross-sectional area of lamp}}$$

$$= \frac{4\rho L_A}{\pi d^2} \tag{3.11}$$

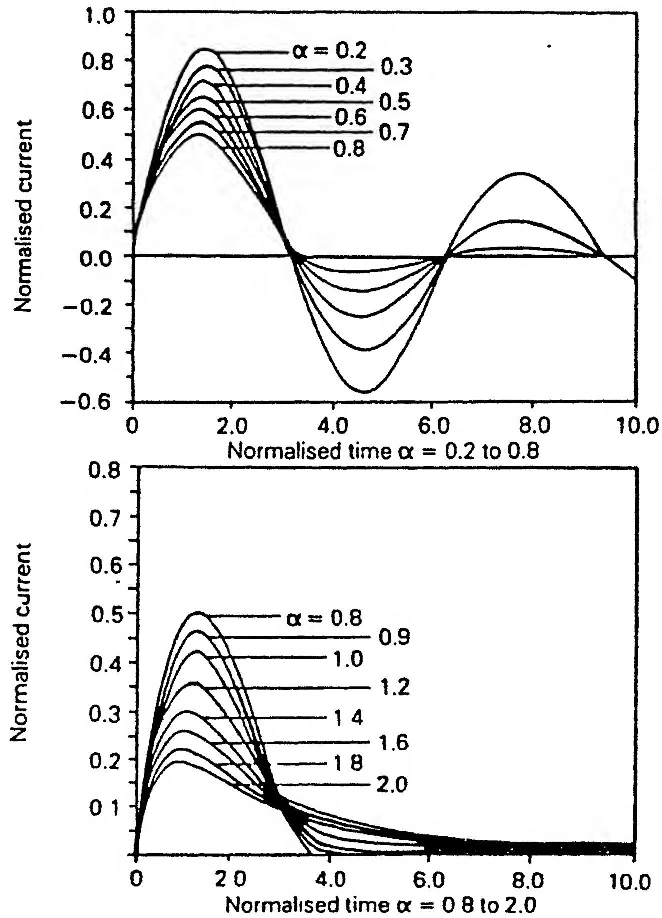


FIG:11 CURRENT CURVES FOR DIFFERENT VALUES OF α

where ρ is resistivity of plasma (Ohms-cm) and can be quantified from the following table,

ρ	t
0.015	$\leq$ 100 μs
0.020	$>$ 100 $\leq$ 1000 μs
0.025	$>$ 1000 μs

Calculation of Network Components for our design :

From our rod (10 mm ϕ) the maximum energy which can be extracted within the safe limits is around 6J. Above this there is a danger of rod damage. As can be seen from Fig. 4 to get an output energy of 6J we have to dump 2.4KJ of energy into the flashlamps. As will be discussed later, the power supply for our amplifier consists of two independent charging banks connected to two flash-lamps in series. Since we require that the total energy dumped in the flashlamps should be 2400J, so each charging bank should store 1200 J of energy. Thus pulse energy required (E_o) = 1200J in the pulse width of T = 450 μs. The parameters of the lamp to be used are L_A = 15 cm, d = 1 cm, P = 450 Torr (default fill pressure of Xenon), N = 450 (Xenon fill).

Therefore by eqn. (3.3)

$$K_o = 19.2 \text{ ohms (amps)}^{1/2}$$

We require a critically damped pulse, therefore α = 0.8. The values of the circuit components required to run this lamp in the way specified may now be calculated.

From eqn. (3.9)

$$t = 150\ \mu s$$

Since we are using two flashlamps in series so the total impedance constant is

$$K_o = 19.2 + 19.2$$

$$= 38.4 \text{ Ohms (amps)}^{1/2}$$

$\therefore$ From eqn. (3.7)

$$C \approx 200\ \mu f.$$

From eqn. (3.6)

$$L \simeq 110\ \mu H$$

From eqn. (3.5)

$$V_o \simeq 3.5 \text{ KV}$$

From eqn. (3.8)

$$Z_o = 0.74 \text{ Ohms.}$$

From eqn. (3.11)

$$Z_L = 0.38 \text{ Ohms}$$

(Since $t = 150\ \mu s$ so $\rho = 0.020$ as can be seen from table)

Since we have two flashlamps in series, the effective impedance Z_L for our case is ~0.76 ohms.

From eqn. (3.10)

$$i_{max} \simeq 2.3 \text{ KA}$$

$\therefore$ current density is given by

$$J_{max} = \frac{4i_{max}}{\pi d^2}$$

$$\simeq 3\text{KA/cm}^2$$

3.2 Power Supply

The major components of a power supply employed in a flashlamp-pumped laser are a charging unit, a pulse forming network, and a flashlamp trigger circuit.

Charging Unit

The function of the charging unit is to charge the energy storage capacitor to a selected voltage within a specified time which depends on the desired repetition rate of the laser. The capacitor-charging source usually consists of a transformer followed by a rectifier bridge, a switching element in the primary of the transformer, a current limiting element, a voltage sensor, and control electronics. The transformer and the rectifier bridge provide the required DC voltage for the energy storage capacitor. In order to be able to vary this voltage and, therefore, to obtain a variable output energy from the laser, a semiconductor switch is usually included in the primary circuit of the transformer. This control element, which can be either a triac, a solid-state relay, or a pair of inverse parallel SCR's, is turned on at the beginning of the charge cycle and tuned off when a preset voltage is reached on the capacitor. Control signals are derived from the capacitor voltage as in conventional DC supply designs. The charging of a capacitor presents a problem in so far as the discharged capacitor constitutes a short circuit. Without a current-limiting device in the power supply the short circuit current is limited only by the resistance of the transformer windings. To protect the rectifier diodes and other components in the circuit, current-limiting circuits are required. The most

straight forward way to charge capacitors is resistance-limited charging from a constant voltage source.

Fig. 12 shows the circuit diagram of power supply unit designed for use to pump linear flashlamps of our Nd:Glass laser amplifier. Essentially these consists of two independent charging banks connected to two flash lamps in series. The power supply essentially consists of a standard power transformer with a solid state relay in the primary, an energy storage capacitor and a trigger circuit. The voltage across the 200 μF energy storage capacitor is sampled by a high-impedance voltage divider, and the voltage is fed to a comparator. If the input is equal to a reference voltage, an output from the comparator will turn off the solid-state relay. This disconnects the transformer from the line so the voltage on the capacitor remains at a constant value. A front panel knob provides prediction of the final capacitor voltage, this is done by changing the reference voltage. The 1kΩ, 100W resistances are used to limit the current in the circuit. Switch RLA/2 is used to discharge the capacitors in case when the decision is made not to fire the flashlamps.

Pulse Forming Network

Flashlamps are operated from a single mesh LC network. The network stores the discharge energy and delivers it to the lamp in the desired current pulse shape. The designing of pulse-forming network has already been discussed in Sec. (3.1).

Inductors for pulse-forming networks are usually air-core coils except for small systems where an iron core may be used.

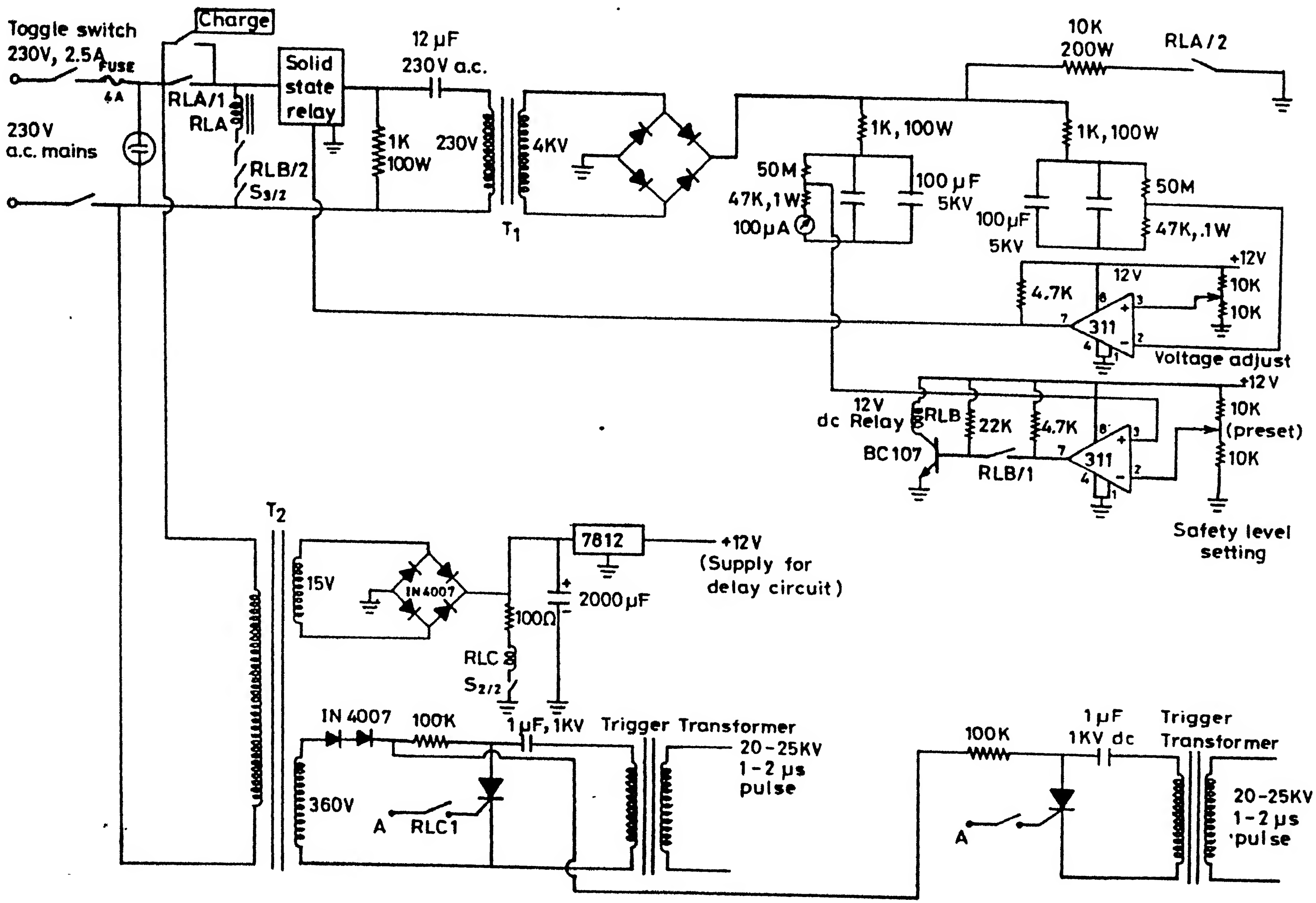


FIG:12 CIRCUIT DIAGRAM FOR POWER SUPPLY UNIT

Energy storage capacitors ranging from 1 to 10 kV and energy levels from 10 to 5000 J are commonly used. Because space is usually at a premium, energy storage capacitors are customarily designed with a higher dielectric stress than is usually employed for conventional DC capacitors. These low inductance capacitors are designed for quick charge and discharge.

Trigger Circuit

The discharge of the stored energy into the flash-lamp is generally initiated by a high-voltage trigger pulse. The function of the trigger signal is to create an ionized spark streamer between the two electrodes so that the main discharge can occur. The initial spark streamer is formed by the creation of a voltage gradient of sufficient magnitude to ionize the gas column. The concept of a voltage gradient is important here, since it implies the existence of a stable voltage reference surface in close proximity to the flashlamp. Regardless of the triggering method used, reliable triggering cannot be achieved without these reference. Usually, an equipotential condition on the outside wall of the tube is achieved through use of a wire wrapped around the flashlamp or by the proximity of the metal parts of the pump cavity. The ignition process can be explained by assuming that areas of the inside glass wall behave as small electrodes capacitively coupled to the reference plane. When the trigger voltage is applied, a discharge takes place between the cathode and the nearby part of the inside wall, which part will then be almost at cathode potential. Next, a discharge takes place between this part of the glass wall and a more remote area still

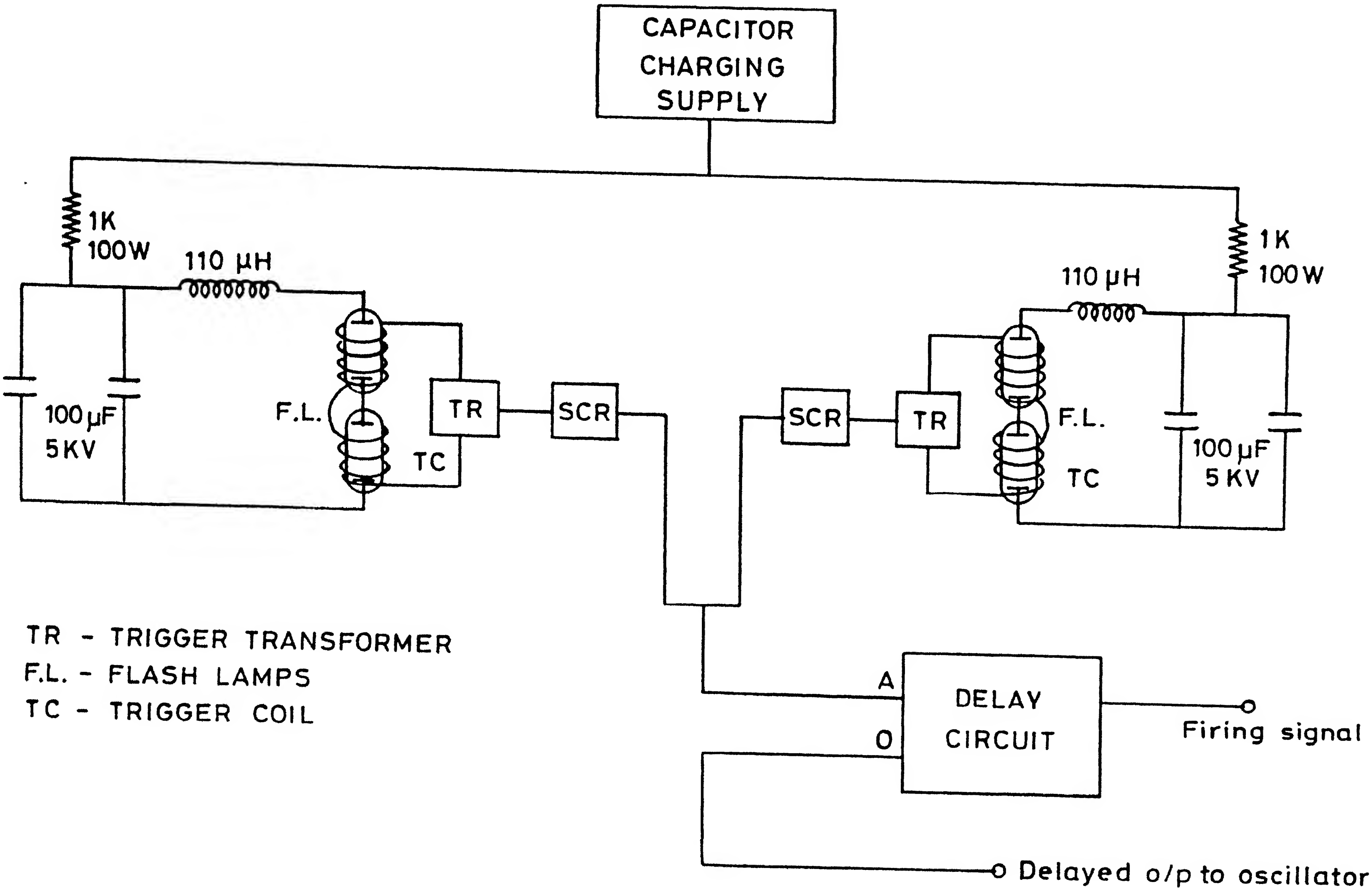
at high potential, and so on until the anode is reached.

In our design, Fig. 12, the flashlamps are fired by external triggering. The trigger pulse is generated by discharging a 1μf, 1kV capacitor through the primary of a trigger transformer using an SCR. The firing of this SCR is controlled by a trigger pulse from the trigger delay network.

Fig. 13 gives the schematic diagram of the amplifier power supply.

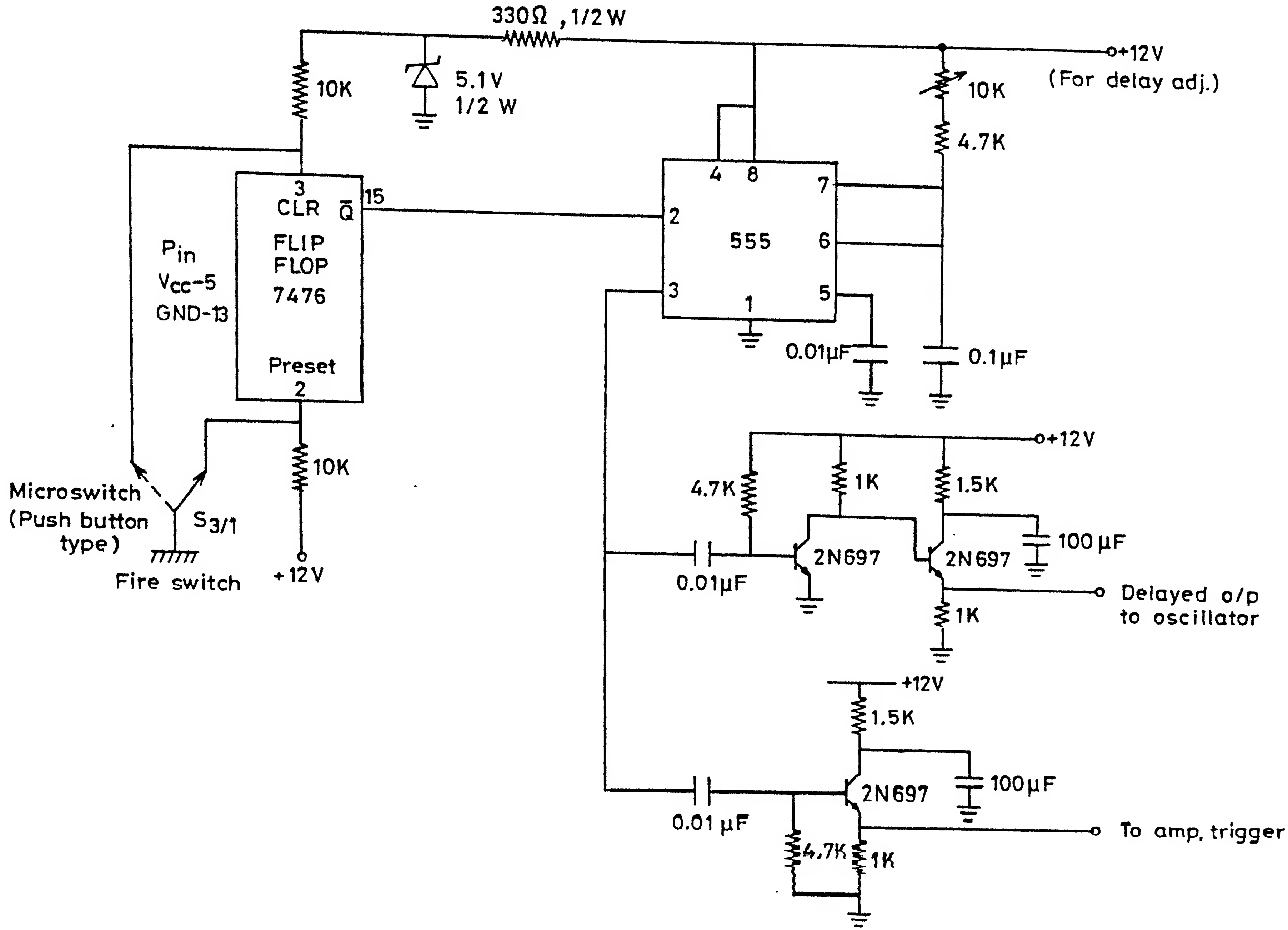
Trigger Delay Network

Fig. 14 shows the trigger delay network circuit which has been designed to control the triggering of our system. Since the firing of the amplifier is advanced with respect to the oscillator firing, a trigger delay network was designed which triggers both amplifier and oscillator at a fixed time delay. This delay can be adjusted to optimized the performance of the system. The trigger delay network, basically consists of a 555 monostable multivibrator which is triggered by a flip-flop using microswitch. When the fire switch is pressed flip-flop gives a trigger pulse and trigger monostable multivibrator. The leading edge and the trailing edge outputs of the monostable after differentiation are used to trigger amplifier and oscillator respectively. The delay can be adjusted by the 10 KΩ potentiometer, which varies the output pulse width of the monostable multivibrator.



TR - TRIGGER TRANSFORMER
F.L. - FLASH LAMPS
TC - TRIGGER COIL

FIG:13 SCHEMATIC DIAGRAM OF THE AMPLIFIER POWER SUPPLY


330Ω ,1/2 W
+12V
(For delay adj.)
10K
5.1 V
1/2 W
10K
4.7K
3
CLR
Q̄
15
FLIP
FLOP
7476
Preset
2
Pin
Vcc-5
GND-13
4
8
7
2
555
6
3
1
5
0.01µF
0.1µF
+12V
4.7K
1K
1.5K
100 µF
2N697
2N697
0.01µF
Delayed o/p
to oscillator
1K
10K
Microswitch
(Push button
type)
S3/1
Fire switch
+12V
+12V
1.5K
2N697
100µF
0.01 µF
To amp. trigger
4.7K
1K

3.3 The Pump Cavity

In solid-state laser, population inversion is obtained by optical pumping with a flash tube or continuous lamp. For better efficiency, the flashtube and the laser rod are combined in a laser pumping cavity, or simply the pump which is, as a rule, a closed optical system where the light emitted by the flashtube is focused by reflectors onto the laser rod. The pump cavity, besides providing good coupling between the source and the absorbing active material, is also responsible for the pump density distribution in the laser element which influences the uniformity, divergence, and optical distortions of the output beam.

The most widely used pump cavity is a highly reflective elliptical cylinder with the laser rod and pump lamp at each focus. the elliptic configuration is based on the geometrical theorem that rays originating from one focus of an ellipse are reflected into the other focus. therefore an elliptical cylinder transfer energy from a linear source placed at one focal line to a linear absorber placed along the second focal line. The elliptical cylinder is closed by two plane-parallel and highly reflecting end plates. This makes the cylinder optically infinitely long.

The Multi-Elliptical Cavity

Since the energy or power delivered to a discharge lamp is limited, schemes to focus the energy from many lamps into a single crystal is employed to extract maximum energy from rod.

The geometrical transfer efficiency, which gives the fraction of the light emitted from the lamp that actually reaches the rod, for the multielliptical cavity is given by [Ref. 2]

$$\eta_{ge} = \frac{100}{\pi}\left[(\alpha_o - \alpha_2) + \frac{C}{d}\,\theta_o\right] \qquad (3.14)$$

The various terms appearing in the expression are shown in Fig. 15. At point P_o the surface of the reflector makes an image of the lamp which exactly fills the laser rod diameter. C is the diameter of the rod and d is the diameter of the lamp.

From the properties of an ellipse and noting, that at P_o, $r_o/s_o = C/d$,

$$\mathrm{Cos}\,\alpha_o = \frac{1}{e}\left[1 - \frac{1-e^2}{2}\left(1 + \frac{C}{d}\right)\right] \qquad (3.15)$$

$$\mathrm{Sin}\,\theta_o = \frac{d}{C}\sin\alpha_o \qquad (3.16)$$

$$\mathrm{Cos}\,\alpha_2 = \frac{\left(\frac{2e}{1+e^2}\right) - \mathrm{Cos}\,\theta_2}{1 - \left(\frac{2e}{1+e^2}\right)\mathrm{Cos}\,\theta_2} \qquad (3.17)$$

and

$$\theta_2 = \pi/n \qquad (3.18)$$

where e is the eccentricity of the ellipse and n = number of partial ellipse. Using eqn. (3.15 - 3.18), η_{ge} can be calculated for any number of partial elliptical cavity provided C/d and e are known. Fig. 16 shows the efficiency of a quadruple elliptical pumping cavity (n=4), as a function of e with C/d as a parameter.

It is seen from Fig. 16 that the efficiency increases with an increase in the ratio C/d. The results of calculations performed

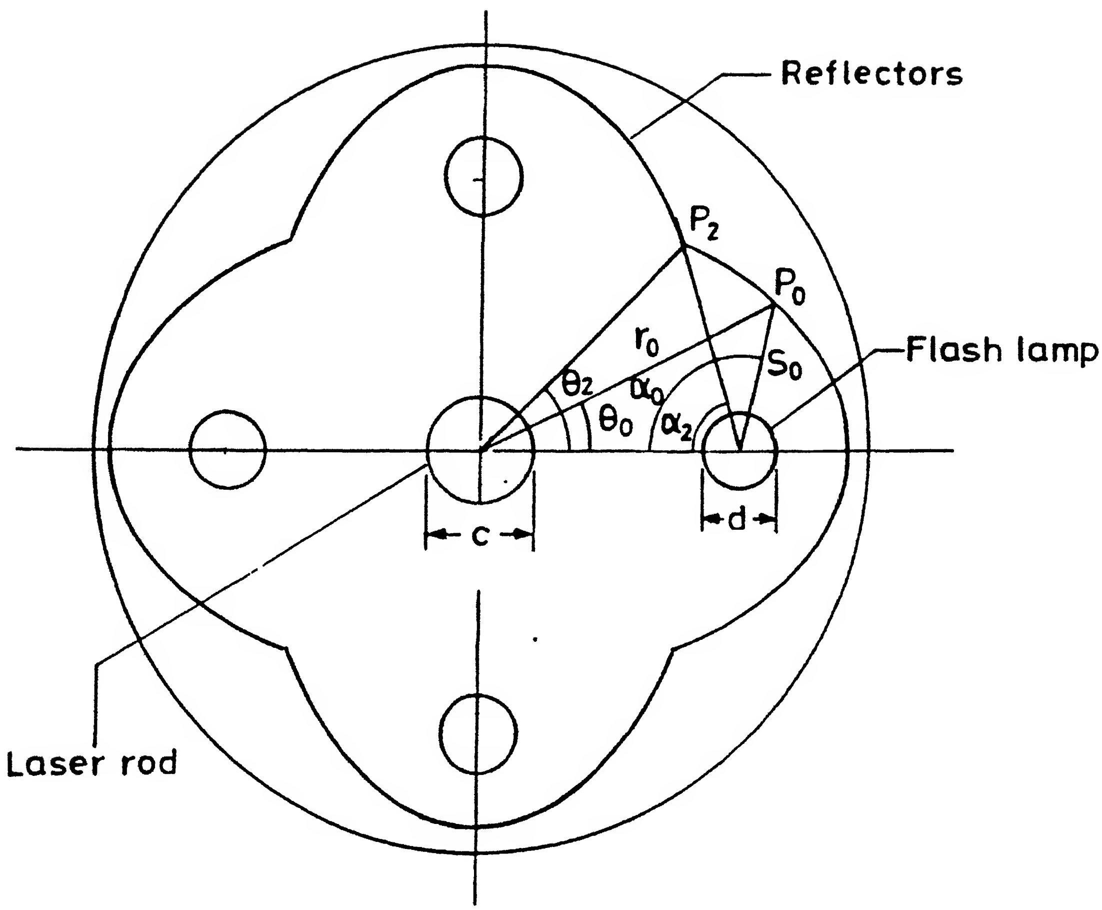


FIG:15 FOUR-CAVITY PUMP UNIT

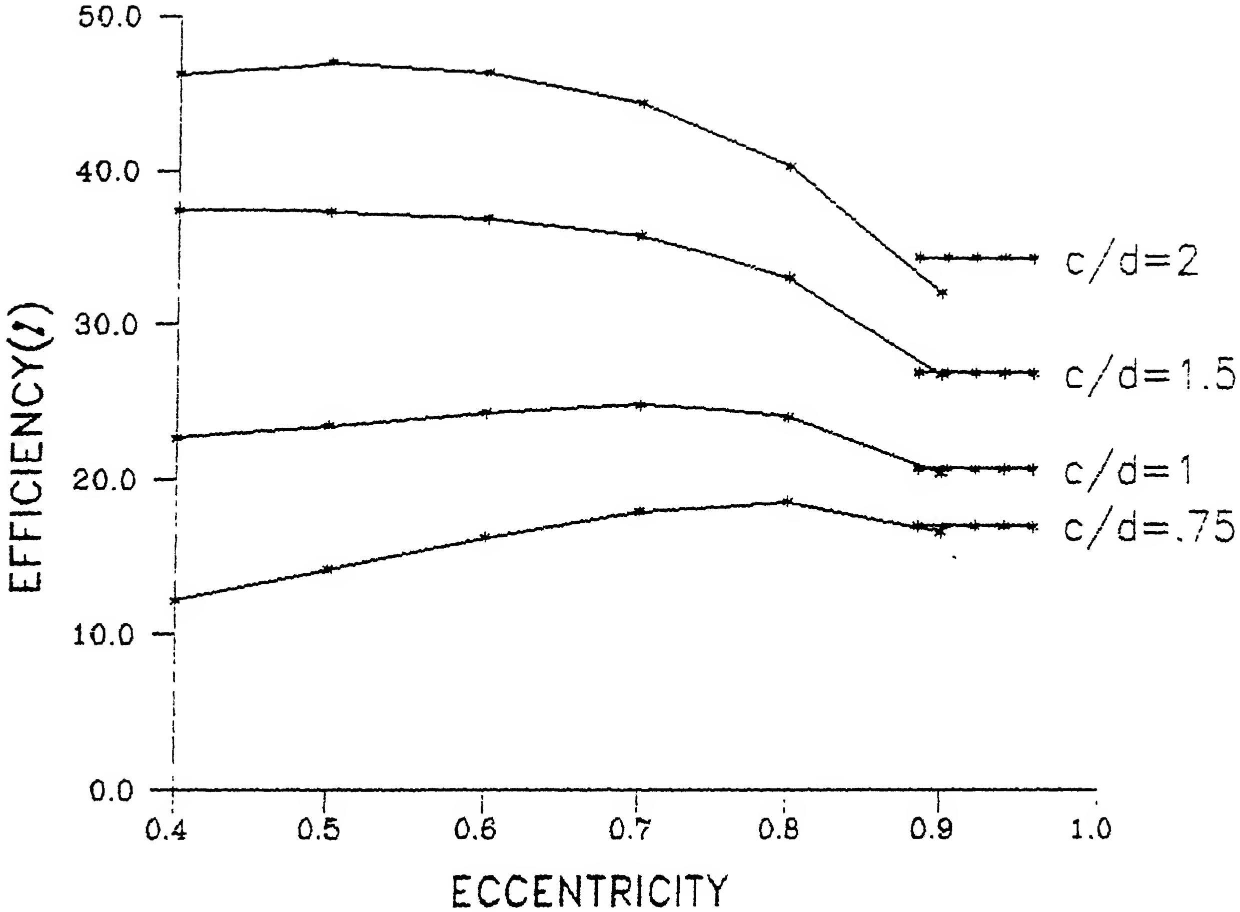


FIG:16 EFFICIENCY OF A QUADRUPLE ELLIPTICAL PUMPING CAVITY

to obtain the efficiency of various multiple cavities with varying sources and rod diameters show that, for equal diameters of the source and the crystal, the single-elliptical cavity has the highest efficiency. However, a cavity with two or more partial-elliptical cavities will allow higher input power, at some sacrifice in overall efficiency, if a high-power output laser is required.

Materials Employed in the Design of Pump Cavity

Since the reflectivity of the metal surfaces as well as the transmission of the cooling fluid in the cavity are wavelength dependent, the spectrum of the pump light incident on the laser rod is different from the source emission spectrum. Ideally, in the transmission of the radiation from the source to the laser rod, one would like to have minimum optical losses in the pump bands of the laser material, and total absorption of all pump energy in spectral regions which do not contribute to the laser output. In this way the thermal heat load and the associated optical distortions in the active material would be kept at a minimum. Particularly undesirable is the ultraviolet content of the pump light, because it causes solarization in most materials. Also undesirable is the formation of ozone by the ultraviolet radiation, because it leads to corrosion of metal parts in the cavity. Pump radiation, which has a longer wavelength than the stimulated emission, does not contribute to the laser output but does heat up the laser crystal and leads to optical distortions. The intensity and spectral content of the pump radiation reaching the laser rod depend on the reflectivity of the cavity walls,

spectral filters placed inside the pump cavity, and the cooling medium.

The metals most commonly employed to obtain specular reflecting surfaces in laser cavities are aluminum, silver and gold. The reflectance versus wavelength of these materials is shown in Fig. 17. [Ref. 1]. The reflective metal surfaces are usually obtained by evaporation, sputtering, polishing, or electro- plating. The reflectance of a good evaporated coating is always higher than that of a polished or electroplated surface.

The cavity walls must have a high reflectivity at the absorption bands of the laser material. Both silver and gold have higher reflectances in the main pump bands of neodymium lasers. For CW-pumped Nd:YAG lasers, where most of the pumping occurs in the wavelength region between 0.7 and 0.9 μm, gold is used exclusively because, in contrast to silver it does not tarnish. For high-power pulsed Nd^{3+} lasers, gold plated cavities are about 25% less efficient than silver plated cavities under otherwise identical conditions. This is because the reflectivity of gold falls drastically at wavelengths shorter than ~0.5 μm, while that of silver remains high down to ~0.35 μm. The green and blue parts of the lamp spectrum, which are significant in pulsed operation, cannot therefore be fully utilized in gold plated cavity. In these systems silver coated reflectors are usually employed. Maintaining the high reflectivity of silver presents a real problem. During the aging of silver in air, a layer of silver sulfide forms on the surface, causing the reflectance to drop. The higher corrosion sensitivity of silver is usually overcome by

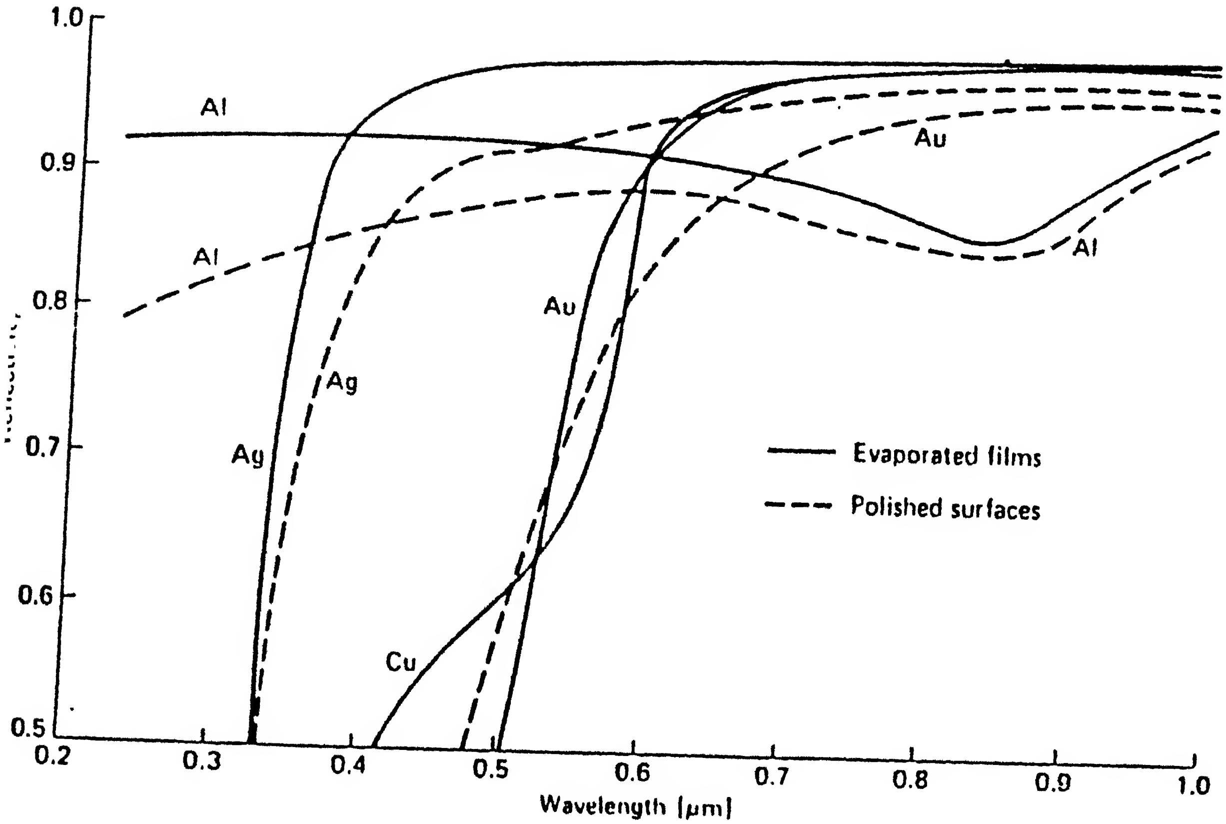


FIG:17 REFLECTIVITY VERSUS WAVELENGTH CURVES FOR METALS COMMONLY USED IN THE DESIGN OF LASER PUMP CAVITIES

coating the reflector with a layer of transparent material, such as SiO_2, or by using an inert cooling fluid.

In focusing geometries the base material for the reflector is either aluminum, copper, or stainless steel. Aluminum is usually employed for light weight systems. Aluminum reflectors in Nd:Lasers require silver plating for pulsed-pumped systems and gold plating for CW-pumped systems. If weight considerations are not too stringent, a better choice for the reflector base material is copper, since copper has a lower thermal expansion, higher thermal conductivity compared to aluminum.

The spectral properties of the cooling fluid can be utilized to remove some of the unwanted pump radiation. Water, if used as a coolant, is very effective in absorbing radiation at wavelengths longer than 1.3 μm. Where absorption of ultraviolet radiation by the laser material must be held to a minimum, potassium chromate, potassium dichromate, or sodium nitrite can be added to the cooling water.

Mechanical design of the Pump Cavity

In our design, laser head consists of glass rod surrounded by 4-linear Xenon flash-lamps (10ϕ x 150 mm) enclosed in a circular cylindrical reflector. The pump cavity consists of two parts that separate along the diameter of the circular reflector Fig. 18. This reflector is made from aluminum. In our design actually we were wishing to make elliptical cavity instead of circular cavity but due to machining problem we were not able to make it.

Fig. 19 shows the cross-sectional view of the pump cavity. The glass rod and the flashlamps are held together in two aluminum end plates (E). These end-plates are fixed in the aluminum base plate (BP). The glass rod (G) is held in position by neoprene `O' rings (A). The `O' rings are held in place by retainer rings (B) made from brass. A pyrex glass jacket (J) is slipped over the laser rod and attached to the end plates by another set of `O' rings (C) and brass retainer rings (D). The `O' rings (A) and (C) enclose a buffer zone through which the filter solution enters the filter jacket. The laser rod is water cooled by circulating the coolant in flow tubes which surround it. The inside of the pumping chamber itself is dry. No cooling arrangement was done for flashlamps. The inlets (I) and outlets (O) for the solution are taken through retainer rings (D). The circular reflectors are then attached to the end plates.

The strong emission of flashlamps in the ultraviolet region, which results in the solarization of the glass, was filtered by circulating in the flow-tube sodium nitrite solution which has excellent cut-off below 4000 A° Fig. 20.

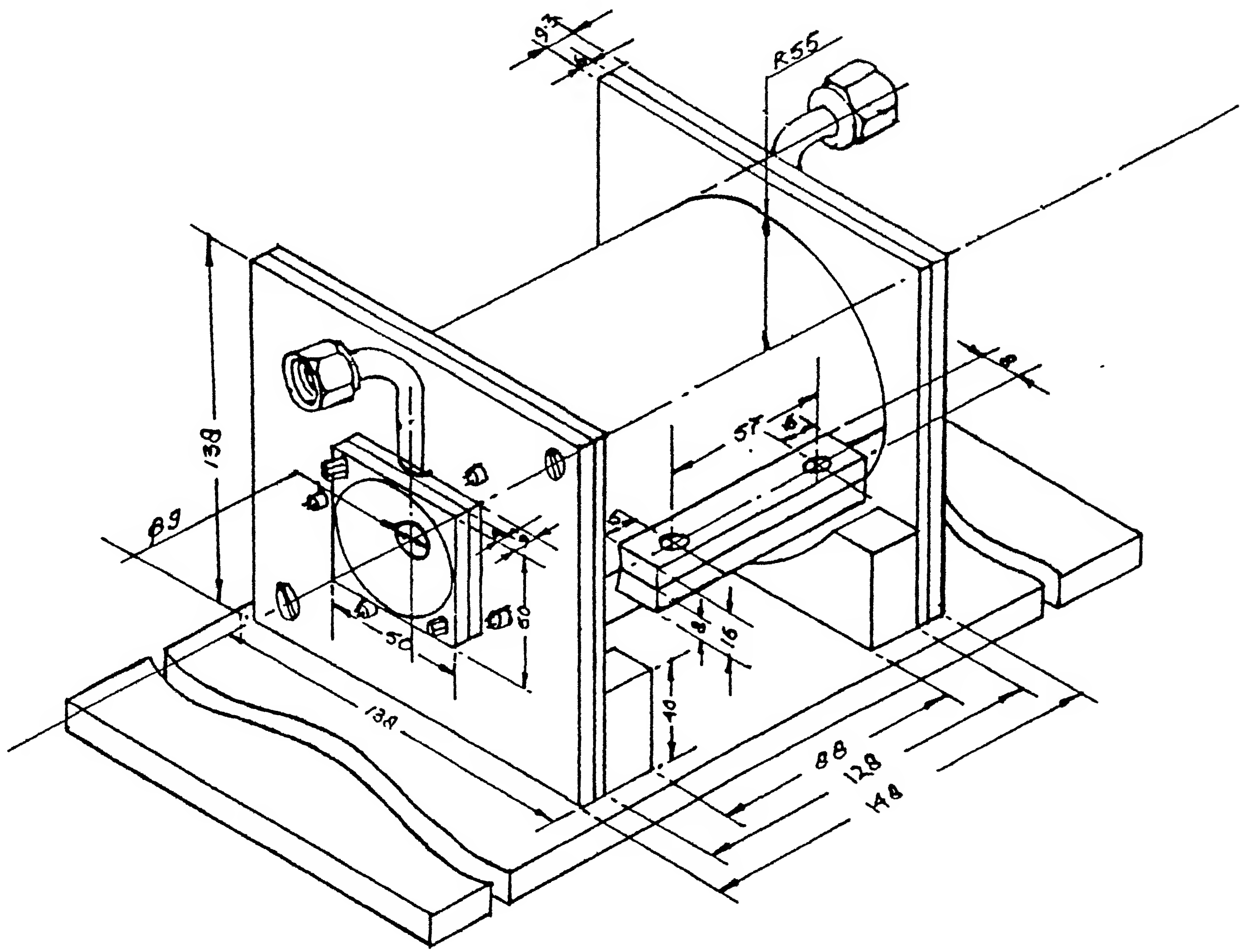
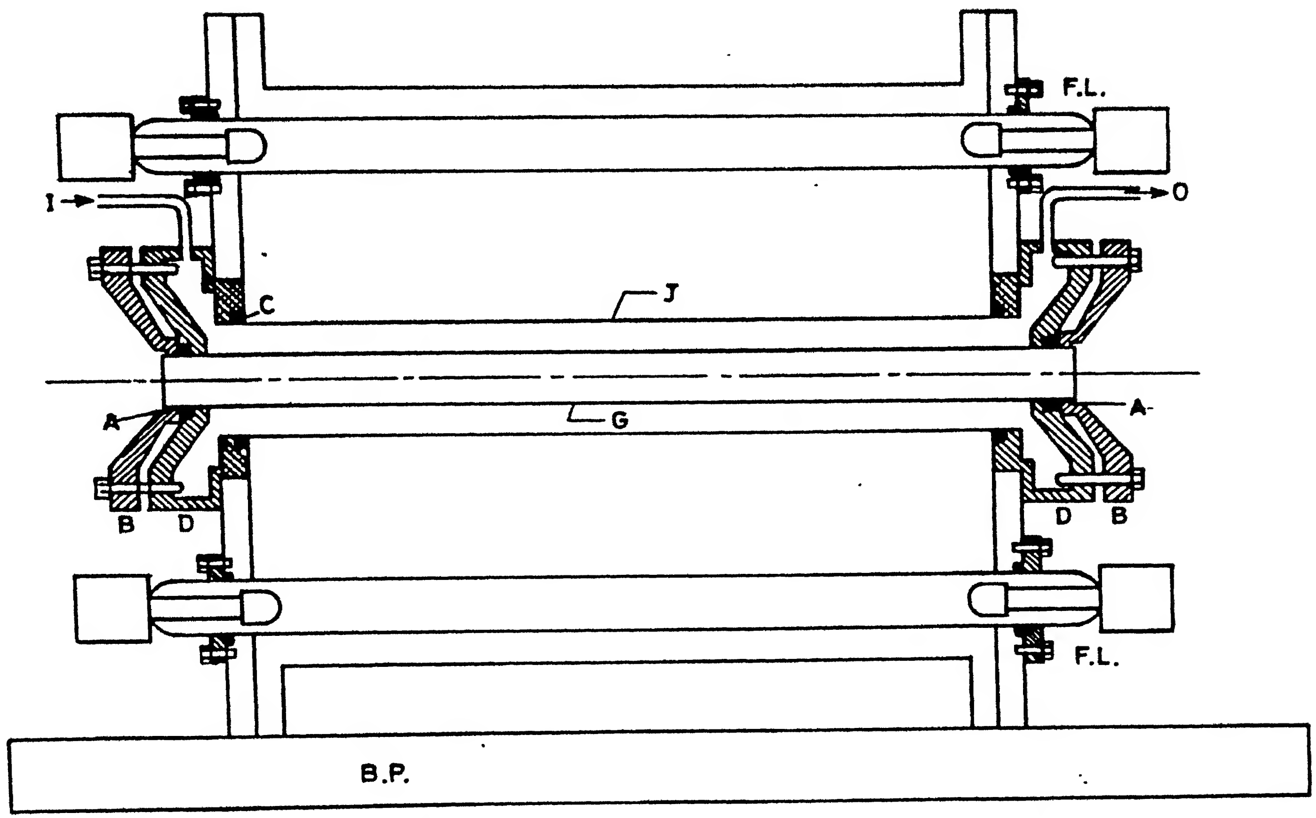


FIG: 18 ISO-METRIC VIEW OF PUMP CAVITY



J-Pyrex glass jacket; G-Glass rod; A, C-'O' rings; B, D-Retainer rings; B.P.-Base plate
F.L.-Flash lamp

FIG: 19 CROSS-SECTIONAL VIEW OF THE PUMP CAVITY

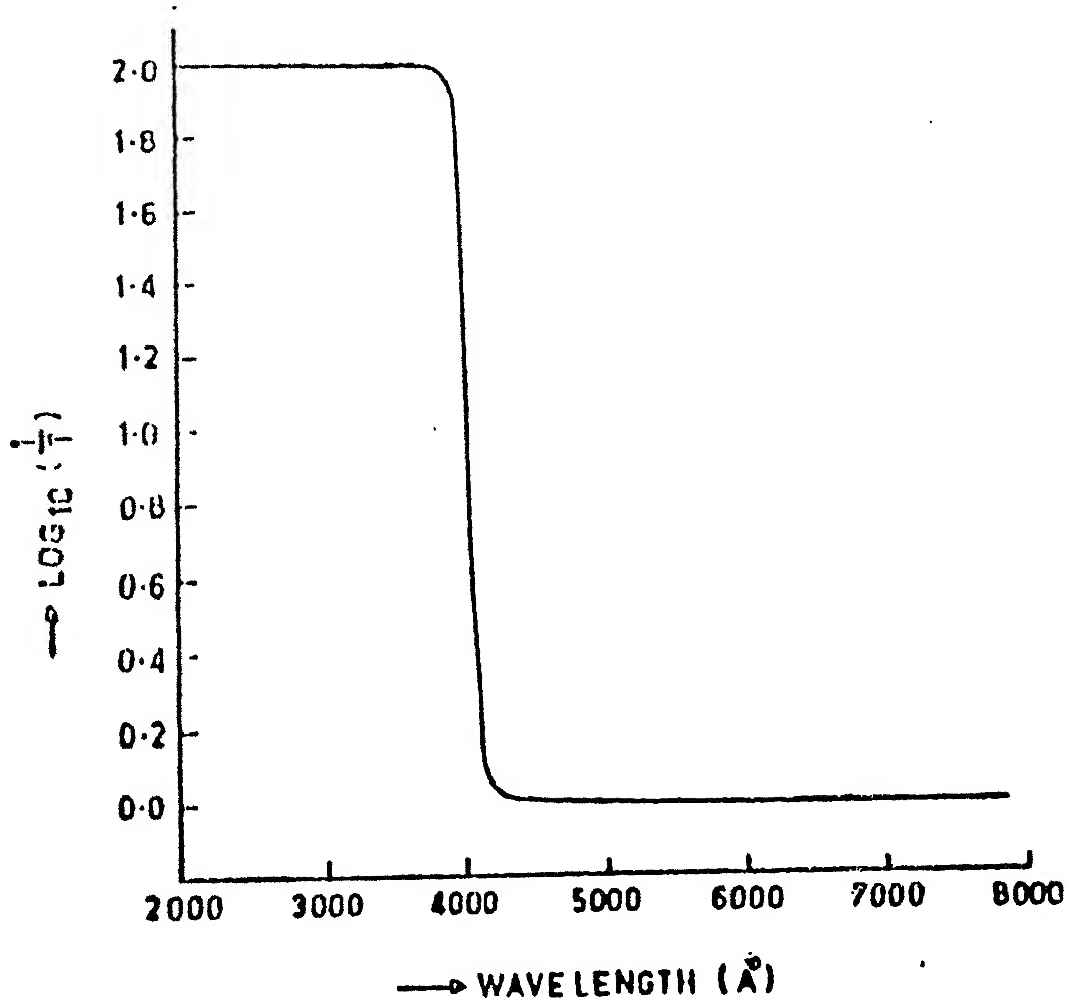


FIG:20 TRANSMISSION CHARACTERISTICS OF SODIUM-NITRITE SOLUTION

[Ref4]

CHAPTER 4

OPTICAL PUMPING EFFICIENCY

INTRODUCTION

A key parameter that determines laser efficiency is the cavity optical pumping efficiency. This efficiency is split up, in somewhat intuitive way, into the product of four factors :

1) the radiative efficiency, which accounts for the fraction of the electrical energy (or power) delivered to the lamp that is actually found as radiative energy (or power) in the useful absorption region of the solid-state material.

2) the transfer efficiency, which gives the fraction of the light emitted from the lamp that actually reaches the rod.

3) the absorption efficiency, which is the fraction of the incident light absorbed by the rod; and

4) the energy (or power) quantum efficiency, which is the fraction of the absorbed energy (power) found as available energy (power) between the upper and lower laser levels.

In this work, we have calculated efficiency factors based on previously mentioned spectroscopic data regarding the laser material, i.e., absorption cross section, absorption coefficient and pump quantum efficiency, and on lamp spectral characteristics. The calculations have been performed for a Nd:glass rod of size 10ϕ x 150 mm pumped by 4-Xenon flash lamps of bore diameter 10 mm and arc length 150 mm, in a quadruple elliptical pump cavity.

Pumping Efficiency Factor

In this section we analytically define and discuss the overall pumping efficiency and the four efficiency factors just referred to [Ref. 7].

A. Overall Pumping Efficiency

The overall pumping efficiency η_p may be defined as the ratio of the energy available between upper and lower laser levels to the electrical energy E entering the lamp. We can thus write

$$\eta_p = \frac{\hbar\,\omega_o \int_V \left[\int_o^{\infty} \left(\frac{dN_2}{dt} \right)_p dt \right] dV}{E} \qquad (4.1)$$

where ω_o is the laser frequency, $(dN_2/dt)_p$ is the number of atoms per unit volume per unit time which are excited to the upper laser level by the pumping process, and where the integral is taken over the rod volume V.

B. Radiative Efficiency

The lamp radiative efficiency η_r may be defined as

$$\eta_r = \frac{\int_{\lambda_1}^{\lambda_2} E_\lambda \, d\lambda}{E} \qquad (4.2)$$

where E_λ is the radiative energy per unit wavelength emitted by the lamp, and the integral is taken over the wave length range λ_1 to λ_2 that is, in fact, useful for pumping the upper laser level.

pump bands of the laser material are present beyond that value, while λ_2 is taken to be slightly shorter than the transition wavelength between the ground and the upper laser levels.

For further calculations, a normalized spectral distribution g_λ of the lamp emission is also introduced as

$$g_\lambda = \frac{E_\lambda}{\eta_r E} \tag{4.3}$$

Note that, according to (4.2) and (4.3), we find that

$$\int_{\lambda_1}^{\lambda_2} g_\lambda d\lambda = 1$$

It should also be noted that both g_λ and η_r strongly depend on the lamp characteristics and on the value of the input energy E.

C. Transfer Efficiency

The transfer efficiency η_t can be defined as

$$\eta_t = \frac{\int_{\lambda_1}^{\lambda_2} E_{e\lambda} d\lambda}{\int_{\lambda_1}^{\lambda_2} E_\lambda d\lambda} = \frac{\int_{\lambda_1}^{\lambda_2} \eta_{ge}\ \eta_{op} E_\lambda d\lambda}{\int_{\lambda_1}^{\lambda_2} E_\lambda d\lambda} \tag{4.4a}$$

where $E_{e\lambda}$ is the energy per unit wavelength entering the rod, η_{ge} is a geometrical transfer factor, and η_{op} takes into account the losses due to the reflection at the walls of the pump cavity, the absorption of the media inside the cavity, and the reflection or scattering at the rod surface. Calculation of η_{ge} has been

already done in section [3.3] and is found to be independent of wavelength. To simplify matters, we will assume η_{op} to be independent of λ and equal to its average value as given by

$$\bar{\eta}_{op} = \int_{\lambda_1}^{\lambda_2} \eta_{op} E_\lambda d\lambda \bigg/ \int_{\lambda_1}^{\lambda_2} E_\lambda d\lambda$$

and, thus, write

$$E_{e\lambda} = \eta_{ge}\,\bar{\eta}_{op}\,E_\lambda = \eta_t\,E_\lambda \tag{4.4b}$$

$\bar{\eta}_{op}$ can be expressed as

$$\bar{\eta}_{op} = r_w(1-r_r) \tag{4.5}$$

where r_w is the reflectivity of the cavity walls at the pump bands, r_r is the reflection losses at the laser-rod surface or at the glass envelopes of the cooling jackets.

D. Absorption Efficiency

The absorption efficiency η_a can obviously be defined as

$$\eta_a = \frac{E_a}{\int_{\lambda_1}^{\lambda_2} E_{e\lambda} d\lambda} \tag{4.6}$$

where E_a is the total energy absorbed in the rod. The energy absorbed per unit wavelength $E_{a\lambda}$ can be written as

$$E_{a\lambda} = E_{e\lambda}\left[1 - e^{-2\alpha(\lambda)R}\right] \tag{4.7}$$

where, $E_{e\lambda}$ = energy incident on rod per unit wavelength; 2R = diameter of the laser rod., in cm.; $\alpha(\lambda)$ = rod absorption

coefficient, in cm^{-1}.

Integrating eqn. (4.7), over the wavelength range λ_1 to λ_2 will give the total energy absorbed by the rod.

$$E_a = \int_{\lambda_1}^{\lambda_2} E_{e\lambda} \left(1 - e^{-2\alpha(\lambda)R}\right) d\lambda \tag{4.8}$$

Substituting eqn. (4.8) in (4.6) gives

$$\eta_a = \frac{\int_{\lambda_1}^{\lambda_2} E_{e\lambda} \left(1-e^{-2\alpha(\lambda)R}\right) d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{e\lambda} d\lambda} \tag{4.9}$$

From eqn. (4.4b) and (4.9) we have

$$\eta_a = \frac{\int_{\lambda_1}^{\lambda_2} E_{\lambda} \left(1-e^{-2\alpha(\lambda)R}\right) d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{\lambda} d\lambda}$$

or

$$\eta_a = \frac{\int_{\lambda_1}^{\lambda_2} \frac{E_{\lambda}}{E} \left(1-e^{-2\alpha(\lambda)R}\right) d\lambda}{\int_{\lambda_1}^{\lambda_2} \frac{E_{\lambda}}{E} d\lambda} \tag{4.10}$$

E. Energy (Power) Quantum Efficiency

The power (energy) quantum efficiency η_{pq} may be defined as the ratio of the power (energy) available between the upper and

lower laser levels to the absorbed power (energy). We can thus write

$$\eta_{pq} = \frac{\hbar\omega_o \int_V \left(\frac{dN_2}{dt}\right)_p dV}{P_a} \tag{4.11}$$

where P_a is the power absorbed by the rod. The pump power absorbed per unit volume per unit wavelength at a given point of the laser rod is given by

$$\left(\frac{dP_{a\lambda}}{dV}\right) = \frac{\alpha(\lambda)C_o}{n}\rho_\lambda \tag{4.12}$$

where $\alpha(\lambda)$ = Rod absorption coefficient; n = refractive index of the rod; C_o = velocity of light in vacuum; ρ_λ = pump spectral energy density at that point of the rod.

The quantity ρ_λ at the radial co-ordinate r inside the rod can be written as

$$\rho_\lambda = nf\,\rho_{o\lambda} \tag{4.13}$$

where, $f = f(\alpha R,\ r/R)$ is a normalized function; $\rho_{o\lambda}$ = pump spectral energy density that would have been present at the same point of the rod for $n = 1$ and $\alpha = 1$.

To calculate the quantity ρ_λ, we recall that the rod lateral surface acts as a perfect diffuser. In this case $\rho_{o\lambda}$ is related to the spectral intensity I_λ entering the rod by the relationship

$$\rho_{o\lambda} = \frac{4I_\lambda}{C_o} = \frac{2P_{e\lambda}}{\pi C_o R l} \tag{4.14}$$

where $\rho_{e\lambda}$ = power entering the rod per unit wavelength; ℓ = length of the laser rod.

From eqns. (4.12), (4.13), (4.14), (4.4b) and (4.3), we have,

$$P_a = \frac{2}{\pi R \ell} \eta_t \eta_r P \int_V \int_{\lambda_1}^{\lambda_2} \alpha f(\alpha R, r/R)\, g_\lambda \, d\lambda dV \qquad (4.15)$$

here

$$g_\lambda = \frac{P_\lambda}{\eta_r P}$$

The quantity $\left(\frac{dN_2}{dt} \right)_p$ can be obtained in terms of the more commonly used pump quantum efficiency $\eta_{q\lambda}$, which is defined as the ratio of the number of atoms raised to the upper laser level to the number of pump photons absorbed. We thus have

$$\left(\frac{dN_2}{dt} \right)_p = \int_{\lambda_1}^{\lambda_2} \frac{\eta_{q\lambda} \left(\frac{dP_{a\lambda}}{dV} \right) d\lambda}{\hbar\omega} \qquad (4.16)$$

By eqns. (4.12), (4.13), (4.14) and (4.4b), we have

$$\left(\frac{dN_2}{dt} \right)_p = \frac{2}{\pi R \ell} \eta_t \eta_r P \int_{\lambda_1}^{\lambda_2} \frac{\eta_{q\lambda} \alpha f(\alpha R, r/R) g_\lambda \, d\lambda}{\hbar\omega} \qquad (4.17)$$

Substituting (4.15) and (4.17) in (4.11) we have

$$\eta_{pq} = \frac{\int_V \int_{\lambda_1}^{\lambda_2} \eta_{q\lambda} \, \alpha f(\alpha R, r/R)\, g_\lambda \frac{\lambda}{\lambda_o} \, d\lambda \, dV}{\int_V \int_{\lambda_1}^{\lambda_2} \alpha f(\alpha R, r/R)\, g_\lambda \, d\lambda dV}$$

or,

$$\eta_{pq} = \frac{\int_{\lambda_1}^{\lambda_2} \eta_{q\lambda} \; \alpha\bar{f}(\alpha R) \; g_\lambda \frac{\lambda}{\lambda_o} \, d\lambda}{\int_{\lambda_1}^{\lambda_2} \alpha\bar{f}(\alpha R) \; g_\lambda \, d\lambda} \tag{4.18}$$

where λ_o is the laser wavelength and $\bar{f}(\alpha R)$ is the average value of $f(\alpha R, r/R)$ over the rod volume V. $\bar{f}(\alpha R)$ as a function of αR is plotted in Fig. 21 [Ref. 7].

In the case of pulsed pumping all equations considered above still hold, provided that powers and power densities, are replaced by the corresponding integrated variables, i.e., energy and energy density.

Since by (4.3)

$$g_\lambda = \frac{E_\lambda}{\eta_r \; E} = \frac{P_\lambda}{\eta_r \; P}$$

the energy quantum efficiency can be written from (4.18) as

$$\eta_{pq} = \frac{\int_{\lambda_1}^{\lambda_2} \eta_{q\lambda} \; \alpha\bar{f}(\alpha R) \; \frac{E_\lambda}{E} \frac{\lambda}{\lambda_o} \, d\lambda}{\int_{\lambda_1}^{\lambda_2} \alpha\bar{f}(\alpha R) \; \frac{E_\lambda}{E} \, d\lambda} \tag{4.19}$$

Eqns. (4.2), (4.4a), (4.10) and (4.19) give the desired expressions for the four pump efficiency factors considered in this work. Note also that from eqns. (4.1), (4.2), (4.4a), (4.6) and (4.11) it can be readily verified that the overall pumping efficiency η_p is given by the product of the four efficiency factors, i.e.,

$$\eta_p = \eta_r \eta_t \eta_a \eta_{pq} \tag{4.20}$$

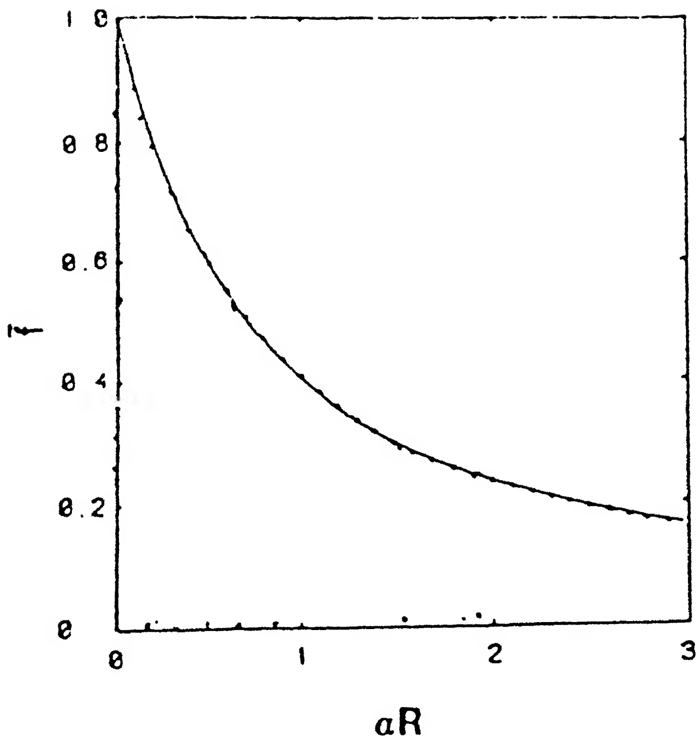


FIG:21 NORMALISED AVERAGE PUMP ENERGY DENSITY $\bar{f}$ IN THE ROD AS A FUNCTION OF R [Ref7]

(e) = 0.45

TABLE I

λ = 1062.3 mm

Pump quantum efficiency $\eta_{q\lambda}$ = 0.90 (ref. 8)

Refractive index of glass rod (n) = 1.555

λ (nm)	$\Delta\lambda$ (nm) (Band width)	α (cm^{-1})	$\frac{E_\lambda}{E}$ $(nm)^{-1}$ $\times 10^{-4}$	$\overline{F}$	λ/λ_o
880	40	1.35	7.2	0.52	0.828
810	50	3.87	12.4	0.26	0.762
740	40	3.68	8.8	0.28	0.697
685	20	0.35	8.2	0.82	0.645
580	64	7.0	11.0	0.15	0.546
533	32	1.97	10.8	0.42	0.502
510	20	1.00	10.2	0.62	0.480
470	40	0.31	13.0	0.84	0.442
430	6	0.66	11.8	0.72	0.405
355	26	3.09	11.0	0.30	0.334

From Fig. 16, which shows the efficiency of a quadruple elliptical pumping cavity as a function of e, it can be seen that

$$\eta_{ge} = 23\% \qquad \text{for } e = 0.45 \text{ and } C/d = 1$$

From eqn. (4.5)

$$\overline{\eta}_{op} = r_\omega \, (1-r_r)$$

where, r_ω = reflectivity of cavity walls = 0.95 for silver

= 0.85 for Aluminum.

r_r = fresnel losses at the laser rod surface

$$= \frac{(n-1)^2}{(n+1)^2}$$

$$= 0.047$$

$\therefore \bar{\eta}_{op} = 0.905$ for Ag

$= 0.81$ for Al.

$\therefore \eta_t = 21\%$ for Ag

$= 19\%$ for Al.

3. Absorption Efficiency

From eqn. (4.10)

$$\eta_a = \frac{\int_{\lambda_1}^{\lambda_2} \frac{E_\lambda}{E} (1-e^{-\alpha(\lambda)})\, d\lambda}{\int_{\lambda_1}^{\lambda_2} \frac{E_\lambda}{E}\, d\lambda}$$

as 2R = 1 cm.

Substituting the values of E_λ/E, $\Delta\lambda$ and α from table I, we get

$$\eta_a = 78\%$$

4. Energy Quantum Efficiency

From eqn. (4.19),

$$\eta_{pq} = \eta_{q\lambda} \frac{\int_{\lambda_1}^{\lambda_2} \alpha\bar{f} \quad \frac{E_\lambda}{E} \frac{\lambda}{\lambda_o}\, d\lambda}{\int_{\lambda_1}^{\lambda_2} \alpha\bar{f}\, \frac{E_\lambda}{E}\, d\lambda}$$

Since the pump quantum efficiency $\eta_{q\lambda}$ for Nd:glass is found to be independent of λ and have a value ~0.90 [Ref. 8].

Substituting the values of E_λ/E, $\Delta\lambda$, α, $\bar{f}$ and λ/λ_o from table I,

we get

$$\eta_{pq} = 54\%$$

Overall Pumping Efficiency

From eqn. (4.20)

$$\eta_p = \eta_r \eta_t \eta_a \eta_{pq}$$

$$\therefore \quad \eta_p = 3.18\% \qquad \text{for Ag}$$

$$= 2.88\% \qquad \text{for Al.}$$

Thus only 2.88% of the electrical energy pumped into the lamps is converted into the energy available between the upper and lower laser levels.

CHAPTER 5

CONCLUSIONS

We have reported a design of Nd:glass amplifier for Nd:YAG laser which gives a maximum of 125 MW of power in a 8 ns pulse at a wavelength of 1.06 μm. The designing has been done to extract a maximum power of 625 MW in a 8 ns pulse from this oscillator-amplifier configuration. The amplifier was designed for single shot operation (one shot in 5 minutes), as large amount of heat is generated in the pumping process since the thermal conductivity of glass is low. For the extraction of maximum energy from the amplifier it was designed to operate in gain-saturation mode. The output characteristics of the amplifier are discussed. Theoretically the gain of the amplifier increases with pump energy but in practice efficiency decreases as pump energy increases. This degradation is due to heating or i^2R loss in each flash lamp/pulse forming network. As the voltage increases, peak current increases leading to significant losses due to resistive heating and physically proportionally less of the initial stored energy is dissipated by the flash lamps. Also the transmittivity of the flash lamp plasma decreases with pump energy which results in the absorption of the redirected radiation by the flash lamp which is incident on it. The power supply for the excitation of Xenon flashlamps is designed and discussed. The power supply was designed to dump a maximum of 2.4 KJ of energy into the flashlamps. The analysis of the pulsed lamp driving circuit has been done and the values of network components for our system were calculated. The lamps were triggered externally by discharging a 1 μf, 1 KV capacitor through the primary of a trigger transformer

using SCR. A trigger delay network was designed to control the triggering of YAG-oscillator as well as of glass-amplifier. The triggering of the amplifier was done earlier with respect to the oscillator triggering. This delay can be adjusted by the trigger delay network. To redirect the radiation from the flashlamps on the laser rod, pump cavity was designed which was fabricated in CELT Workshop. The pump cavity consists of a glass rod surrounded by a glass jacket in which the cooling fluid flows. Surrounding this rod are the 4-linear Xenon flashlamps which are used to pump the rod. Behind the flashlamps is a circular cylindrical reflector for redirecting radiation emitted in directions other than towards the rod, back towards the glass rod. The circular cylindrical reflector of the pump cavity was coated with aluminum. Sodium nitrite solution was circulated around the glass rod to protect it from the ultra-violet radiation from the lamps.

The amplifier was aligned in such a way that the input beam nearly fills the amplifier rod. The end faces of the amplifier rod was slightly tilted to avoid any reflected radiation from going back to the oscillator. We were not able to test the performance of this oscillator-amplifier configuration due to the non-availability of Xenon flashlamps.

The four-efficiency factors and the overall efficiency for our amplifier design are calculated. The overall efficiency for our amplifier system was found to be 3.18% for silver coated reflectors and 2.88% for aluminum coated reflectors. The transfer efficiency was calculated by assuming the reflectors to be elliptical. In our design the reflectors are circular which

efficiency for our system is somewhat lower than the value quoted above.

Future Work

The efficiency of the system can be improved by circulating fluorescent dyes around the glass rod. These dyes absorbs in the spectral region in which the neodymium ions do not absorb and becomes fluorescent at one of the pump bands of Nd^{3+}. This results in a more efficient utilization of the flashlamp light output. These dyes also prevent solarization due to their absorption in the ultraviolet region. Rhodamine 6G dissolved in ethanol is identified as best dye for Nd:glass giving 50% improvement in the efficiency [Ref. 9].

The efficiency can be improved further by making the reflector elliptical and coating it with silver with a layer of transparent material, like SiO_2, over it.

This amplifier system is designed for the use in experiments on laser produced plasmas and the related diagnostics.

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